Technical Report REMR-CS-61
June 1999

US Army Corps of Engineers
Waterways Experiment Station

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

An Evaluation of Equipment and Procedures for Tensile Bond Testing of Concrete Repairs

by Alexander M. Vaysburd, Structural Preservation Systems, Inc.
James E. McDonald, WES

Approved For Public Release; Distribution Is Unlimited

Prepared for Headquarters, U.S. Army Corps of Engineers

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

PRINTED ON RECYCLED PAPER

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Technical Report REMR-CS-61
June 1999

An Evaluation of Equipment and Procedures for Tensile Bond Testing of Concrete Repairs

by Alexander M. Vaysburd

Structural Preservation Systems, Inc.
3761 Commerce Drive
Suite 414
Baltimore, MD 21227

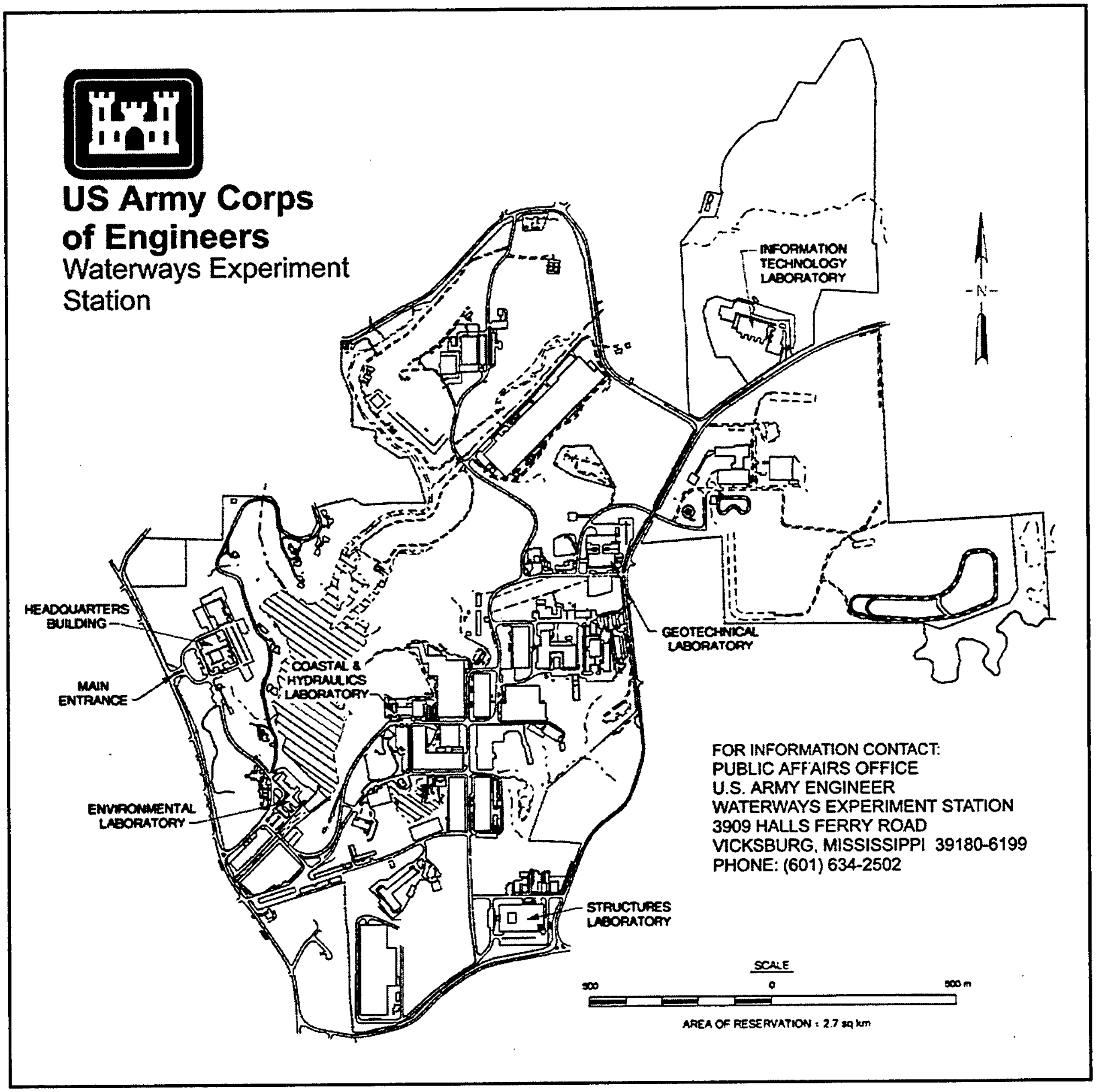
James E. McDonald

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit 32637



Waterways Experiment Station Cataloging-in-Publication Data

Vaysburd, Alexander M.
An evaluation of equipment and procedures for tensile bond testing of concrete repairs / by Alexander M. Vaysburd, James E. McDonald ; prepared for U.S. Army Corps of Engineers.
84 p. : ill. ; 28 cm. — (Technical report ; REMR-CS-61)
Includes bibliographic references.
1. Core drilling — Testing. 2. Binders (Materials) — Testing — Methodology. 3. Concrete construction — Maintenance and repair. I. McDonald, J. E. (James E.) II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Repair, Evaluation, Maintenance and Rehabilitation Research Program. V. Title. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; REMR-CS-61.
TA7 W34 no.REMR-CS-61

Contents

List of Figures

List of Tables

Preface

The study reported herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Unit 32637, "Evaluation of Existing Repair Materials and Methods," for which Mr. James E. McDonald, Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

The REMR Technical Monitor is Mr. M. K. Lee, HQUSACE. Dr. Tony C. Liu (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee. Mr. William F. McCleese (retired), WES, was the REMR Program Manager. Mr. McDonald is the Problem Area Leader for Concrete and Steel Structures.

The study was performed by Structural Preservation Systems, Inc., Baltimore, MD, under contract to WES. The study was conducted under the direct supervision of Mr. McDonald and general supervision of Dr. Paul F. Mlakar, Chief, Concrete and Materials Division, and Mr. Bryant Mather, Director, SL.

At the time of publication of this report, Commander of WES was COL Robin R. Cababa, EN.

The authors would like to acknowledge the substantial contribution of Mr. Miroslav Vadovic, Structural Consultant, in the theoretical analysis of depth of coring; Mr. Ruben Bernal, Structural Preservation Systems, Inc., Illinois Office, for his dedication and hard work during the field testing in Florida, Illinois, and Arizona; and Ms. Margo Gray, Structural Preservation Systems, Inc., Corporate Office, for her assistance in the completion of the report.

Discussions in this report relating to any product named must not be construed as a testimonial or endorsement of that product. As a consequence, readers are cautioned not to make reference in an advertisement to any tests that have been made.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	metres
inches	25.4	millimetres
miles (U.S. statute)	1.609347	kilometres
pound (force) inches	0.1129848	newton metres
pounds (force) per square foot	47.88026	pascals
pounds (mass)	0.45359237	kilograms

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain kelvins (K) readings, use: K = (5/9) (F - 32) + 273.15.

1 Introduction

Background

Concrete repair and rehabilitation commonly include removing unsound concrete and replacing it with repair or overlay materials. No matter what repair material is chosen, one of the key requirements of a repair system is the ability to provide an adequate bond between the repair and existing concrete substrate that remains intact throughout its service life.

When a repair material is applied to a substrate, the difference in the properties of the two materials will affect bond strength development and bond stress distribution. This mismatch can be acute in concrete repairs where a new repair material mixture is applied to an old concrete. Of particular relevance are differences in shrinkage, elastic modulus, and thermal movement.

The strength and integrity of the bond, which depends upon the physical and chemical characteristics of the phases (substrate, repair material, and possible bonding agent) and surface preparation, must be capable of withstanding the stresses imposed on and the processes of deterioration associated with the concrete structures. The bond is principally considered to be due to adhesion, although mechanical interlock also makes a contribution. Simplistically, the repair may be considered as a three-phase composite system: substrate, repair, and bond zone. The local properties of the repair phase and the substrate in the bond zone (vicinity of the interface plane) are usually different from those of existing concrete and repair material.

In situ quality assurance and studies of bond property require test methods that can both quantify a bond-strength parameter and identify a failure mode. There have been numerous investigations of the bond of cementitious systems, and many of these have been concerned with the development of a suitable test.

Bond strength of repair materials has been measured both in laboratory and field tests. A brief overview of some of the test methods for determining the bond of repair materials to existing concrete substrate is presented.

In an evaluation of repair materials with regard to selection criteria, a number of adhesion/bond test methods were discussed, including direct tension, pull-off,

direct shear, flexure, and slant shear (Rizzo and Sobelman 1989). A compilation of studies of each method was summarized by Knab (1988).

Several test methods have been proposed to evaluate bond properties and the performance of repair materials in general. Undoubtedly, tensile bond tests are gaining in popularity because of their relative simplicity and the ability to meet the requirements imposed on in situ bond-strength testing. Tensile test methods can be divided into indirect and direct techniques. The following is intended to provide a brief overview of the tensile test method used in the present study.

The pull-off test method is one of the tensile test methods. Unlike the other bond test methods that are used for laboratory testing, the pull-off test can be used in the field for evaluating the bond strength between repair material and parent concrete in a structure. The first modern development of the pull-off concept for strength testing of in situ concrete was undertaken independently in the United Kingdom at Queens University, Belfast (Long and Murray 1984), and in Austria, where it was called tear-off test (Stehno and Mall 1977). This led to "Limpet" test equipment being commercially available in the United Kingdom. Further test equipment has since been developed in several countries, leading to a wide range of test configurations and procedures now being available.

A number of different pull-off tests have been reviewed by CIRIA (McLeish 1993), the majority involving cutting of the repair material interface before loading. Mathey and Knab (1991) studied the bond strength of concrete overlays by using in situ uniaxial tensile tests (pull-off tests with partial coring). Two types of equipment were used in the tests—a hydraulic, uniaxial tensile test apparatus, which was a modification of the ACI 503R field-test apparatus, and a pneumatic apparatus developed at the National Institute of Standards and Technology. In the pull-off tests, cores were drilled through the overlay concrete and about 13 mm past the interface. A steel disk was then glued on the top surface of the core with a high-strength, quick-setting epoxy.

Bungey and Mandandoust (1992) studied the factors influencing pull-off tests in uniform concrete using experiments and numerical (finite element) analyses. For tests where partial cores were drilled, the factors investigated were the elastic modulus of the disk, the thickness/diameter ratio of the disk, and the depth of partial coring. It was found that disks of 50 mm in diameter and 20 mm in thickness and greater may be expected to give comparable results, whether made of steel or aluminum, provided that the depth of coring was at least 20 mm.

An in situ test apparatus has been used to evaluate the bond of repair materials to concrete surfaces at an angle, including horizontal and vertical surfaces Peterson (1990).

In a study to evaluate spall repairs (Collins and Roper 1989), epoxy mortar repairs to damaged concrete specimens were tested by the pull-off method. The study concluded that the critical factor governing the successful repair was the soundness of the repair-substrate interface.

Laboratory experiments were conducted to investigate a number of important factors that influence the test results and their scatter, including surface preparation of existing concrete prior to overlay, depth of coring, deicing salt application, and resistance to freezing and thawing. Test results show that pull-off test methods effectively assess the durability of bond between new and old concrete (Li, Frantz, and Stephens 1997).

Tensile pull-off tests are becoming increasingly favored in site quality control/quality assurance testing, although little standardization has yet occurred. There is no American Society for Testing and Materials (ASTM) standard for in situ uniaxial tensile test methods. The British Standard BS 1881: Part 207 (1992) provides guidelines for the standardization approach for these tests. According to this Standard, the centers of adjacent test positions should be at least two core-hole diameters apart and one diameter from the edge. The thickness of the metal disk should not be less than 40 percent of its diameter. Six valid tests are usually sufficient in each location. The surfaces of the metal disk and the concrete should be carefully prepared to produce a good bond. Before surface preparation, a core with a diameter equal to that of the disk should be cut to the necessary depth. A loading rate of 0.05 ± 0.03 MPa/s should be used. Both the maximum load and the mode of failure (in the concrete or at the interface) should be recorded. The coefficient of variation of a set of measured values at one location under site conditions is likely to be about 10 percent.

The Dutch Standard (1990) deals specifically with tests, including pull-off tests with partial coring.

A European Standard is currently being drafted by CEN TC 104. In this method, a core is drilled through the repair phase to a certain depth (up to 25.4 mm (1 in.)) within the concrete substrate. A metallic disk is glued on the upper surface of the core by means of a suitable epoxy adhesive and then pulled by a tension device, which increases the load until failure, allowing the tensile bond strength to be determined.

There are numerous devices available for direct tensile pull-off tests that vary widely in sophistication and price (from less than $1,000 to $12,500). A notable limitation of this type of test is relatively poor precision, as evidenced by relatively large variation values associated with different types of apparatus. There is a need for field performance data for different types of devices.

The important issue associated with pull-off tests is the depth of the core drilling into the existing concrete. It is suggested that the influence of the steel dolly and reaction frame on test results depends on the depth of coring into the substrate concrete. Ignoring the effect of drilling depth may be one of the main causes of difficulties in reproducing and comparing test results.

Objective and Scope

If the durability of repaired concrete structures is to be considered the main goal of any repair project, then every effort should be made to ensure adequate bonding between repair and existing structure. To that end, the objectives of this study were as follows:

a. To investigate the effect of material properties and environmental conditions on bond strength development for nine repair materials in the previous study.

b. To evaluate three commercially available tensile pull-off testing apparatuses for testing bond. The Germann Instruments Bond-Test kit, Proceq DYNA Z15, and Hilti Test Meter 4 (Modified) by Structural Preservation Systems, Inc., were evaluated by analyzing the magnitude and relative precision of the pull-off strengths, modes of failure, and testing procedures.

c. To study the effect of the drilling depth into the substrate concrete on pull-off test results by comparing theoretical finite element analysis of failure zone stress distribution with measured test results and to recommend optimum depth of core drilling into the existing substrate.

2 Bond Testing

Materials

Tests to assess the in situ long-term adhesion between different repair materials and the substrate concrete when epoxy bonding compound is used were carried out on experimental repairs placed during a study to develop performance criteria for selection of repair materials (Emmons et al. 1998). Testing was performed in three areas located in south Florida, Illinois, and Arizona. Field studies were performed on nine repair materials. The age of the repairs at the time of test was about 3 years.

The materials selected for bond studies, their generic types, and laboratory properties as determined by Poston et al. (1998) are summarized in Table 1.

Each material was used in three experimental repair slabs at each testing site. The bonding agent conforming to ASTM C 881 (ASTM 1995) was used to bond the repair materials to existing concrete. The bond surface was kept dry when the bonding agent was used.

Pull-Off Test Method and Equipment

The pull-off approach is currently gaining in popularity for testing the bond strength of repairs to concrete when used in conjunction with partial coring. Test equipment for this test has been developed in several countries including the United Kingdom, the United States, Denmark, and Switzerland, leading to a wide range of test configurations and procedures now available (McLeish 1993).

Although there are variations in the testing equipment and method of carrying out the pull-off tests, the general procedures can be described as follows (Figure 1):

a. Marking and preparing the test area.

b. Partial coring into the existing substrate perpendicular to the repair surface. In some cases, partial coring is done around the attached loading disc.

Table 1
Repair Material Properties

Material No.	Generic Type	Compressive Strength psi	Tensile Strength psi	Flexural Strength psi	Modulus of Elasticity psi × 10^6	Coefficient of Thermal Expansion millionths/°F	Drying Shrinkage Millionths		Specific Creep @ 1 Year, Millionths/psi	
							28-Day	Peak	Compressive	Tensile
1	Concrete	6,610	451	289	2.8	5.8	178	366	0.451	0.420
2	Concrete	7,180	399	445	3.2	7.8	391	1,032	0.603	0.831
3	Polymer-modified concrete	6,360	513	421	3.7	7.1	479	1,116	1.913	1.449
4	Concrete	11,530	348	779	3.8	8.3	201	703	0.260	0.609
6	Polymer-modified, silica-fume mortar	9,760	323	493	5.3	9.3	301	878	0.872	0.608
8	Polymer-modified, fiber-reinforced mortar	4,060	215	139	2.7	9.2	305	1,109	1.894	3.587
9	Concrete	4,780	323	415	2.5	6.9	429	877	1.301	1.163
10	Polymer-modified concrete	5,230	402	495	4.2	9.9	16	678	2.037	0.072
11	Concrete	9,620	390	503	5.9	7.6	339	641	0.483	0.555

Note: 1,000 psi = 6.895 MPa.

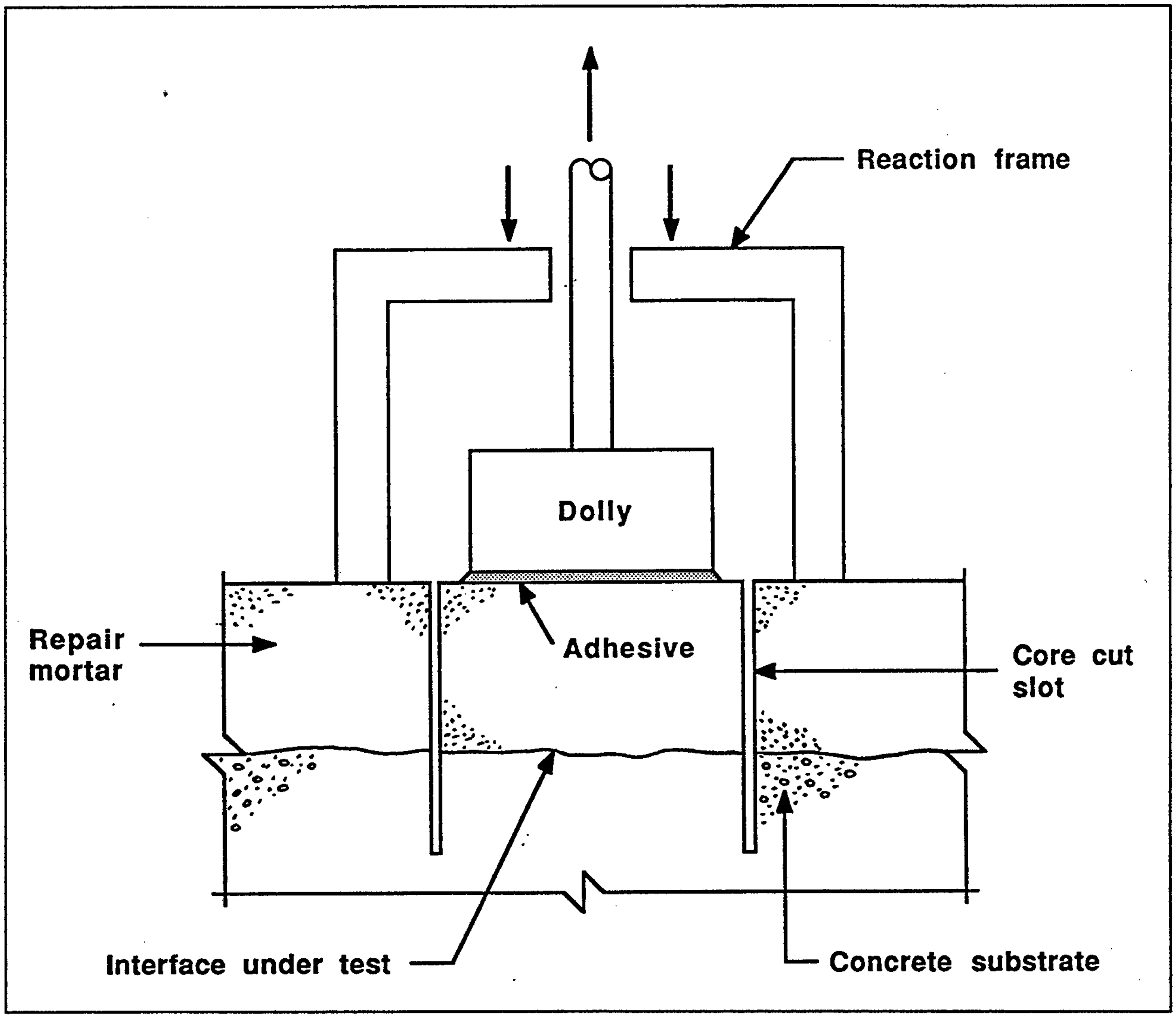


Figure 1. Pull-off test principle

c. Attaching the disc to the core, using an epoxy resin.

d. Attaching a loading frame to the disc. A frame around the disc provides the reaction force to the load.

e. Pulling the disc until the specimens fails.

The failure stress load and the mode of failure are recorded (Figure 2).

The following three types of testing equipment were selected and used in this study.

Germann Instruments Bond Test

The equipment consists of four kits: preparation kit, pull machine kit, corecase kit, and DSV kit (Figure 3).

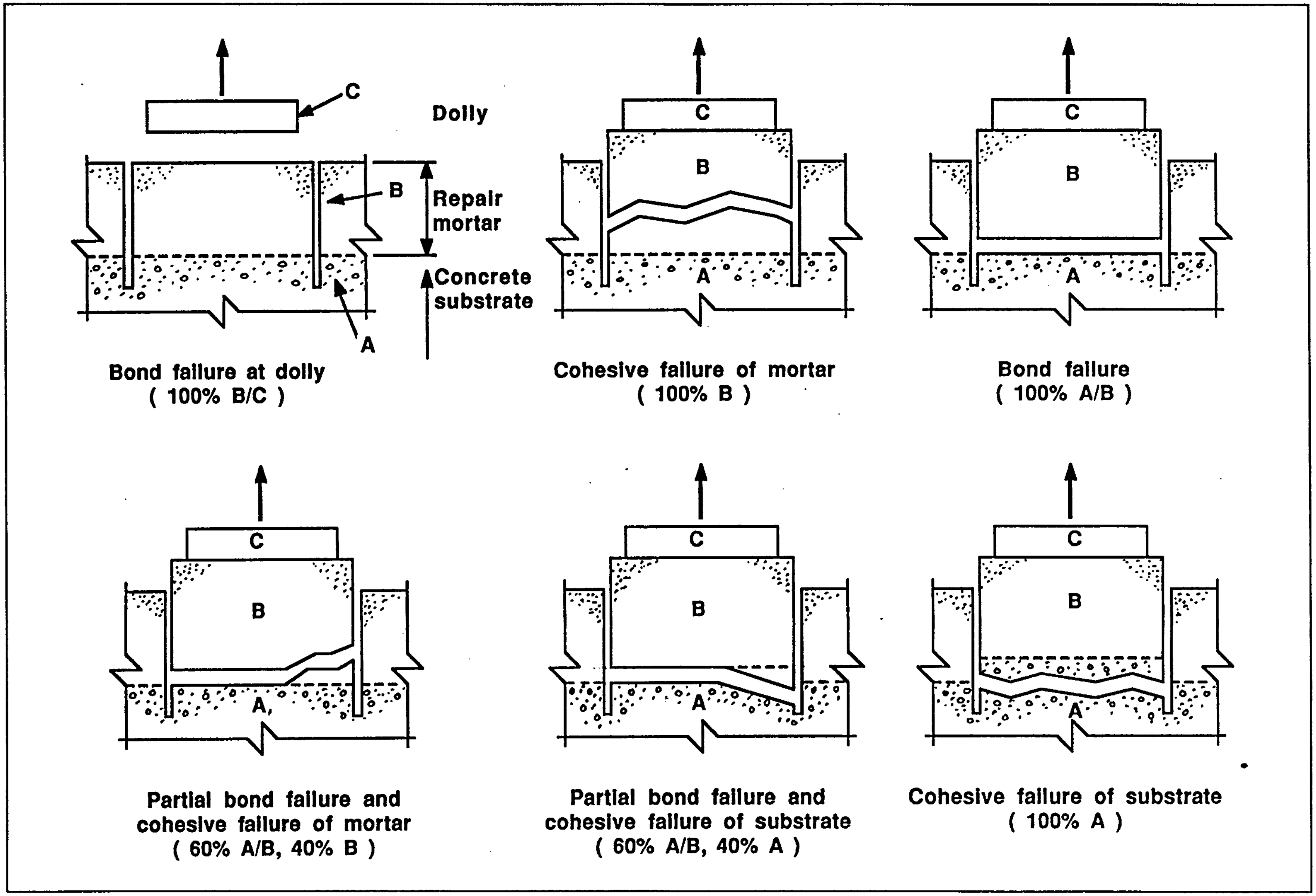


Figure 2. Pull-off test core failure modes

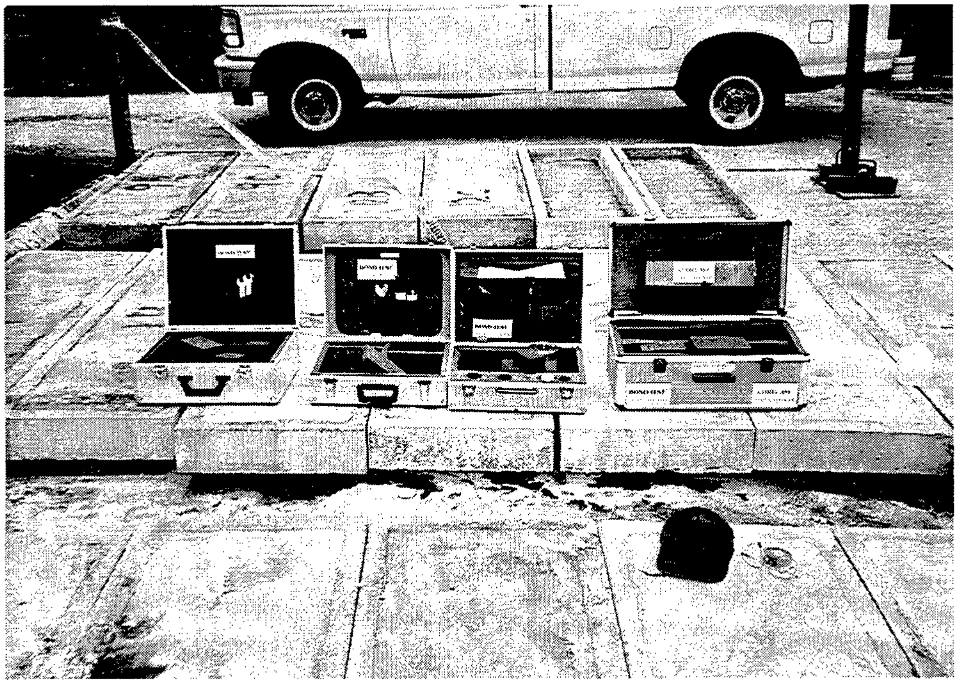


Figure 3. Germann Instruments testing equipment at the jobsite (Florida)

The testing with this equipment takes place as follows:

a. The test surface is planed dry with the diamond surface planing wheel attached to the suction plate (Figures 4 and 5). The corner knob is removed with a grinder and the surface brushed free of all dust (Figure 6).

b. A 75-mm (3-in.) diameter and 30-mm (1.2-in.) thick steel disc is applied with special fastsetting glue to the repair surface inside the suction plate by means of the centering plate and pressed firmly against the surface with the adjustable pliers (Figures 7 and 8).

c. The glue usually hardens in 2 to 5 min depending on ambient temperature.

d. The corecase assembly is fitted around the disc and attached to the suction plate. Drilling takes place to the required depth (Figures 9 and 10).

e. The bond-test hydraulic apparatus is connected to the steel disc resting against the counterpressure frame and loaded by hand (Figure 11). Loading takes place with a constant loading rate to rupture the drilled core at the weakest location.

f. The peak load is recorded to the nearest 0.1 kN (22.5 lb) and transformed to pull-off strength. The pull machine is equipped with an electronic Microprocessor Gauge.

Figure 4. Attachment of vacuum (suction) plate

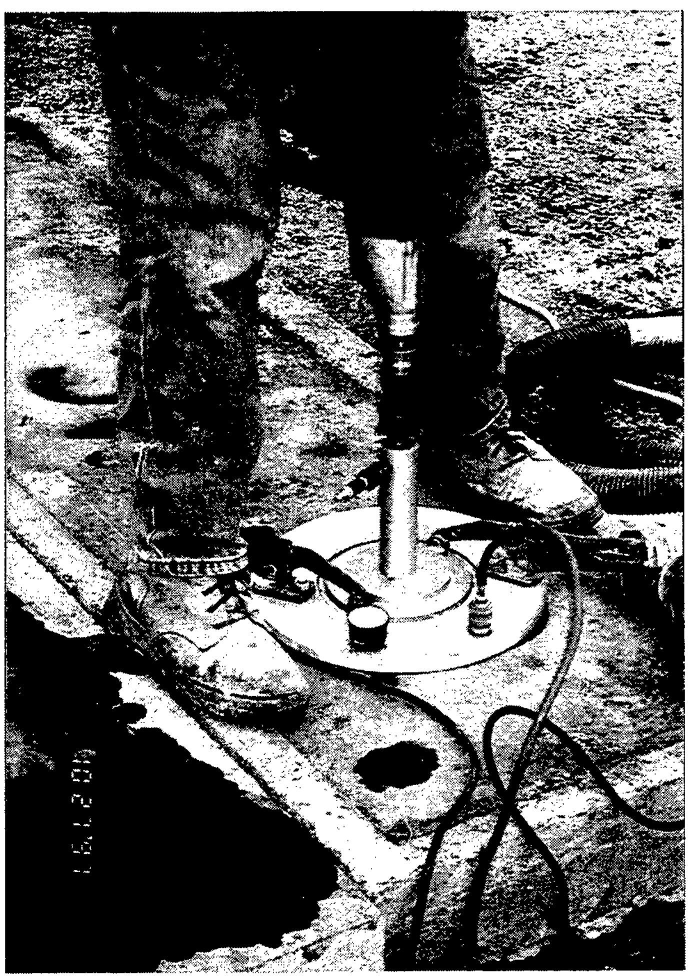


Figure 5. Repair surface grinding

According to the manufacturer, the Germann Instruments equipment allows the automatic application of load at a steady rate of 0.02 MPa (2.9 psi) per second with 0.2-percent accuracy. The peak value at failure is displayed, and test results are stored in the gauge's computer for subsequent printing with a personal computer.

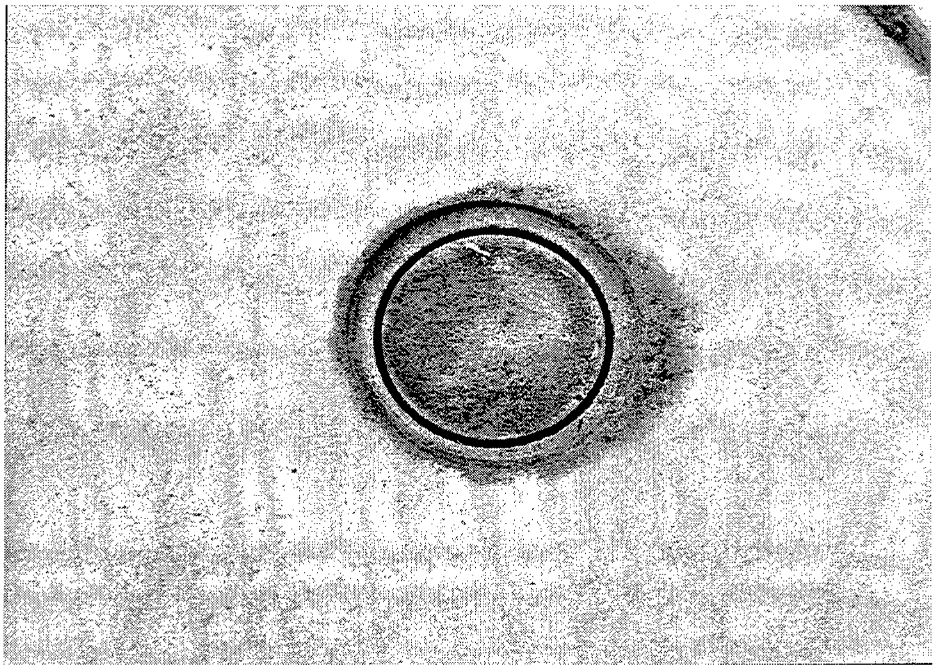


Figure 6. Typical ground surface of partial core

Figure 7. Application of adhesive

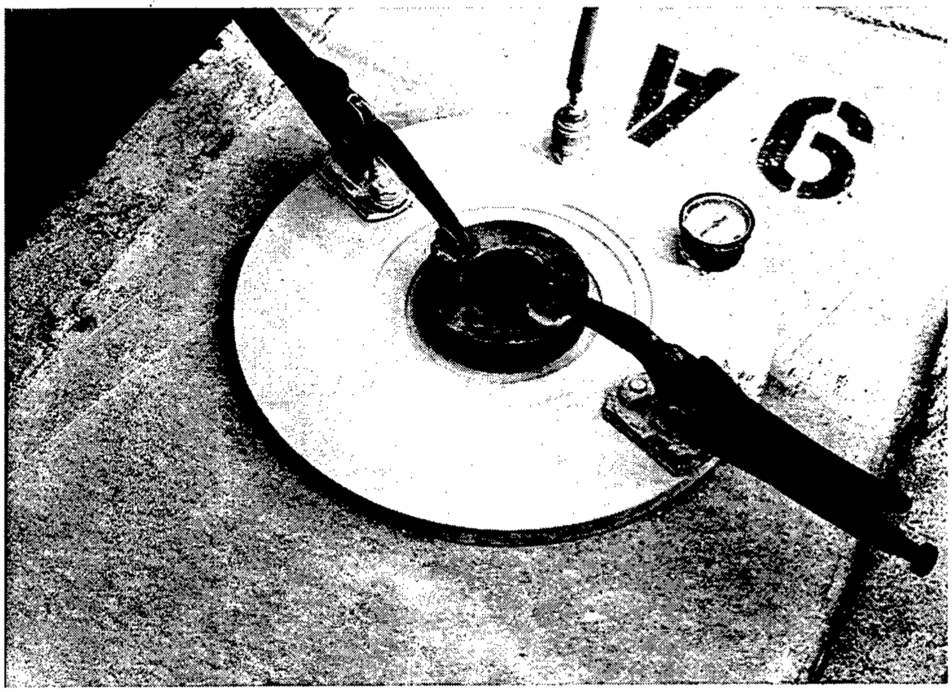


Figure 8. Attachment of steel disc to core surface

Figure 9. Core drilling

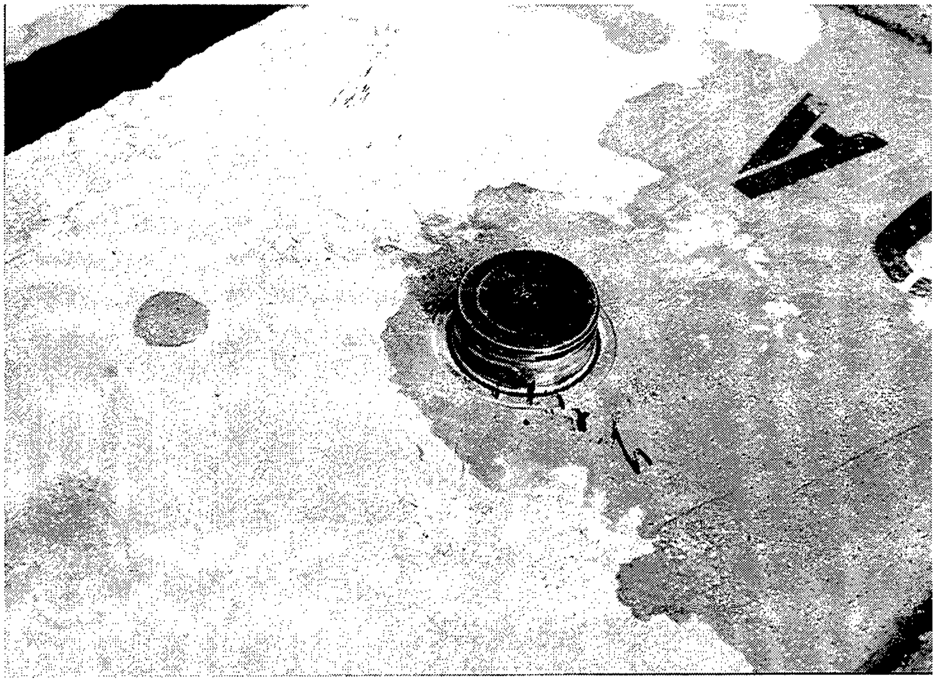


Figure 10. Partial core ready for testing

Figure 11. Germann Instruments pull-off testing

Proceq DYNA Z15 Pull-Off Tester

The apparatus is small, mobile (for use in any location), and has a mass of 3.5 kg (8 lb). The maximum tensile force is 16 kN. The pressure gauge has direct indication in kilonewtons and newtons per square millimetre. Scale graduations are 0.10 kN and 0.10 N/mm^2. The pressure gauge is equipped with a pointer that comes to rest when the specimen fractures.

The standing adjustable legs of the device can be shortened or lengthened to optimize the measurement to the test situation. This allows assurance that the pull-off takes place at right angles. The tester has an easy-running crank drive that allows for jerk-free increases in load. Testing with DYNA Z15 is shown in Figure 12.

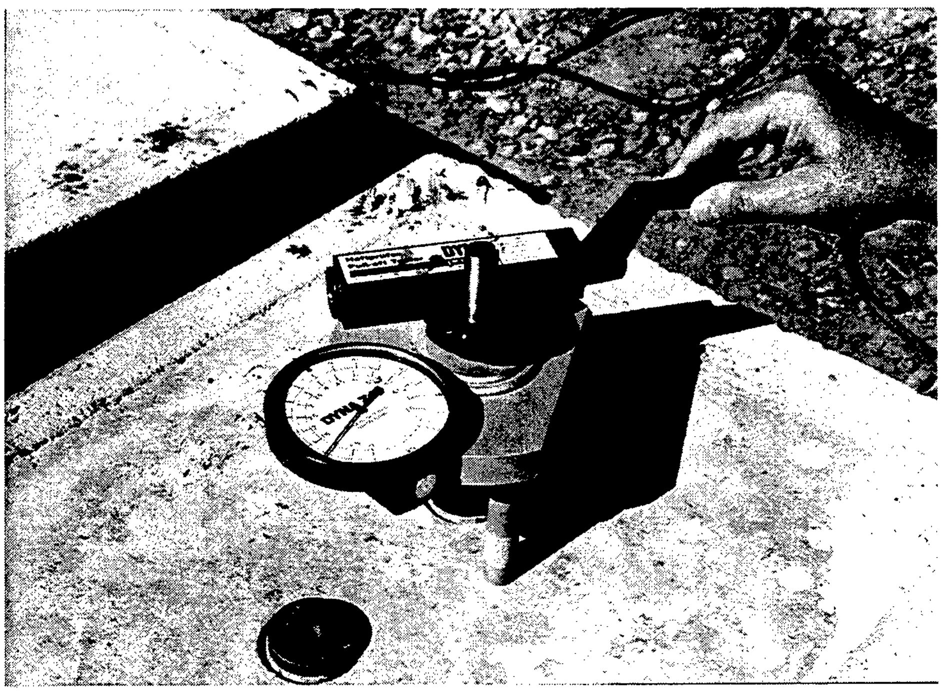


Figure 12. Testing with Proceq DYNA Z15

Drilling was accomplished with a Hilti core drilling machine using a 50-mm (2-in.) internal diameter bit (Figure 13). A 50-mm (2-in.) diam, 25-mm (1-in.) thick steel disc was secured to the surface of the core with a two-component epoxy adhesive. A Hilti HIT C-100 adhesive cartridge with a hand dispenser was used. The test disc was then pulled off with the DYNA pull-off tester (Figure 14).

Hilti Test Meter 4 (Modified)

The Hilti tester is a special apparatus originally designed to measure the pull-out strength of embedded anchors. The apparatus was modified by Structural Preservation Systems, Inc., to measure pull-off bond strengths (Figure 15).

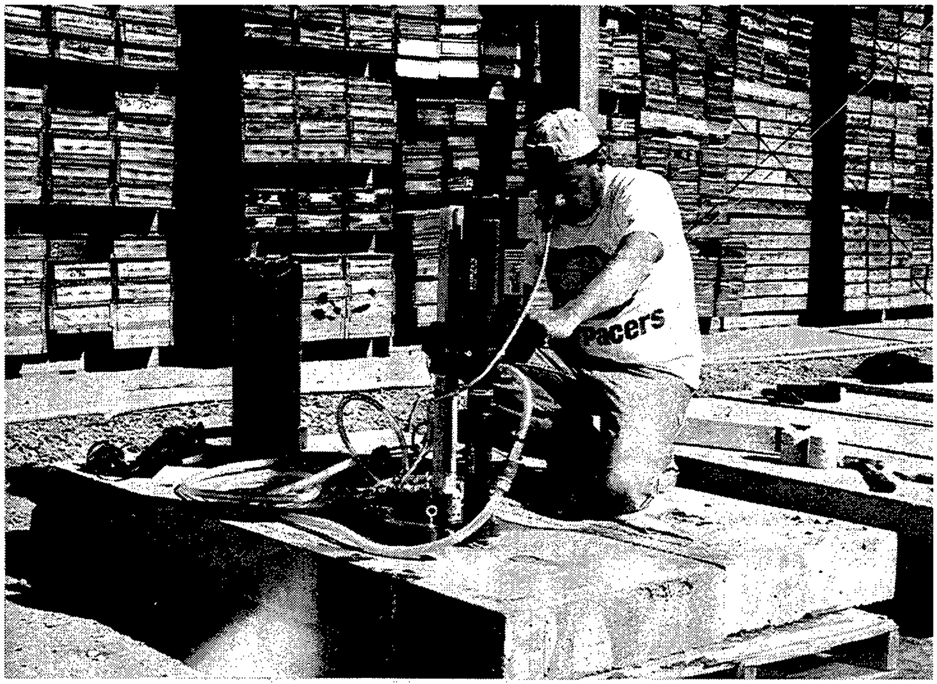


Figure 13. Partial-depth core drilling for testing with DYNA and Hilti


Figure 14. Partial-depth core (left) ready for testing with DYNA

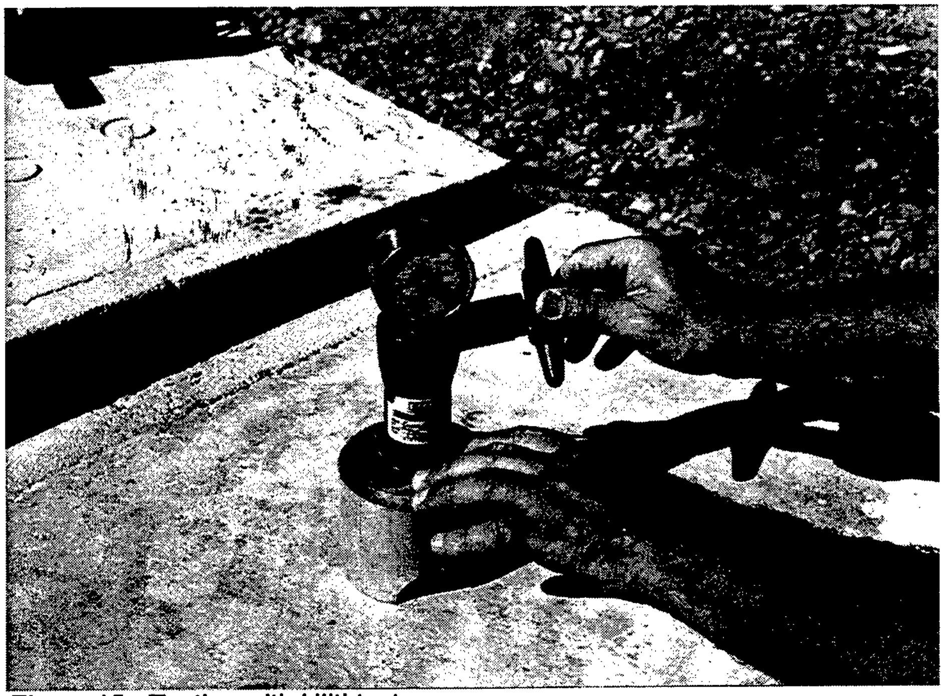


Figure 15. Testing with Hilti tester

The tester has a maximum tensioning force of 8.9 kN (2,000 lb), with gauge scale graduation to 89 kN (20 lb). The device is small, lightweight, and mobile to use in any location. It has an inconvenient hand-wheel drive that does not allow for uniform load increase. It is not equipped with any devices to position it at a right angle to the surface.

The drilling was carried out with a Hilti core drilling machine using a 50-mm (2-in.) internal diameter bit (Figure 13).

A 50-mm (2-in.) diam, 8-mm (5/16-in.) thick steel disc was secured to the surface of the core with a two-component epoxy adhesive. A Hilti HIT C-100 adhesive cartridge with a hand dispenser was used. The test disc was then pulled off with the Hilti tester (Figure 16).

Pull-Off Test Results

In this test series, two 50-mm (2-in.) diam and one 75-mm (3-in.) diam partial cores, 89 mm (3.5 in.) deep, were drilled 13 mm (0.5 in.) below the repair-substrate interface in each experimental repair slab (Figure 17).

A complete listing of all the pull-off test data generated for nine repair materials is shown in Appendix A (Tables A1, A2, and A3). The pull-off strength data together with the respective mode of failure are presented for each of the three testing sites. Each repair material was used in three experimental repair slabs at each testing site (Figures 18-20). Pull-off strengths determined with three different devices on each experimental repair are presented in the tables.

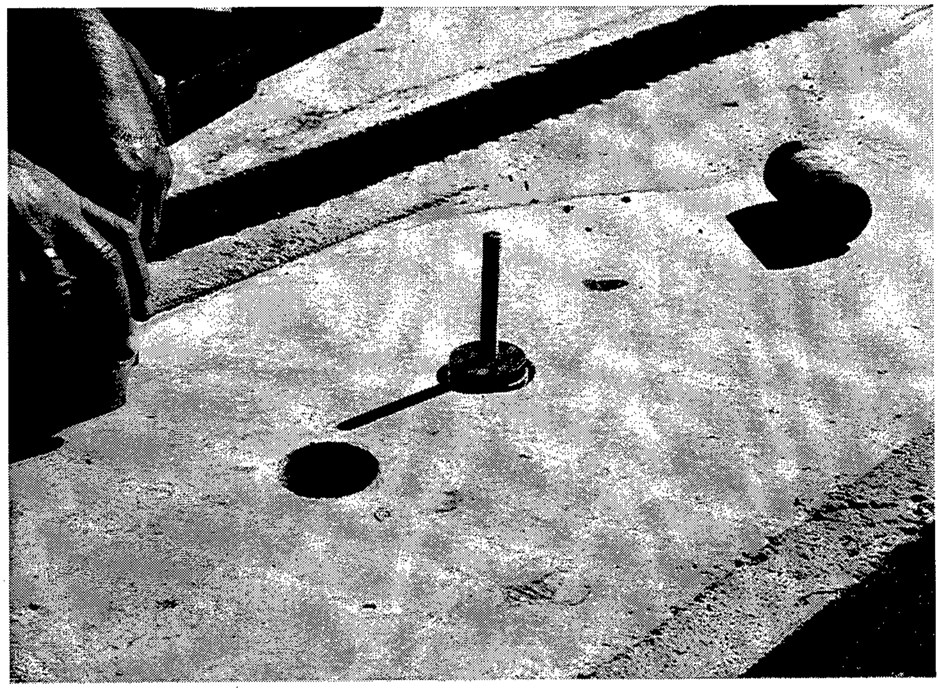


Figure 16. Partial-depth core ready for testing with Hilti tester

The average test results for each material, mode of failure for each specimen, and standard deviation and coefficient of variation (COV) between the three pull-off tests for the same material performed by each testing device are presented in Tables 2-10. Examples of different modes of failure are shown in Figures 21-24.

Pull-off strength data obtained with different devices on the same experimental repairs and with the same device on individual repairs with the same material frequently exhibited wide variations for the same application and exposure conditions. Material No. 6 exhibited the highest average strength of 3.4 MPa (499 psi) when tested in Florida with Germann Instruments equipment. Material No. 9 exhibited the lowest strength of 0.4 MPa (60 psi) when tested in Florida with Germann Instruments equipment and the Hilti tester.

The coefficient of variation between specimens of the same material measured with the same device varied from a minimum of less than 3 percent for Material No. 4 tested with the Hilti tester in Illinois to a maximum of more than 60 percent for Material No. 1 tested with Germann Instruments equipment in Illinois.

An analysis of the modes of failure demonstrates that in the 239 tests performed in this series, 98 failures (41 percent) occurred in the concrete substrate, 61 failures (26 percent) occurred at the repair-substrate interface, 49 failures (20 percent) occurred in the repair material, and 31 failures (13 percent) occurred at the steel disc-repair interface. Of the 31 failures at the steel disc-repair interface, 22 failures occurred within the epoxy adhesive at bond strengths in excess of 1.4 MPa (200 psi).

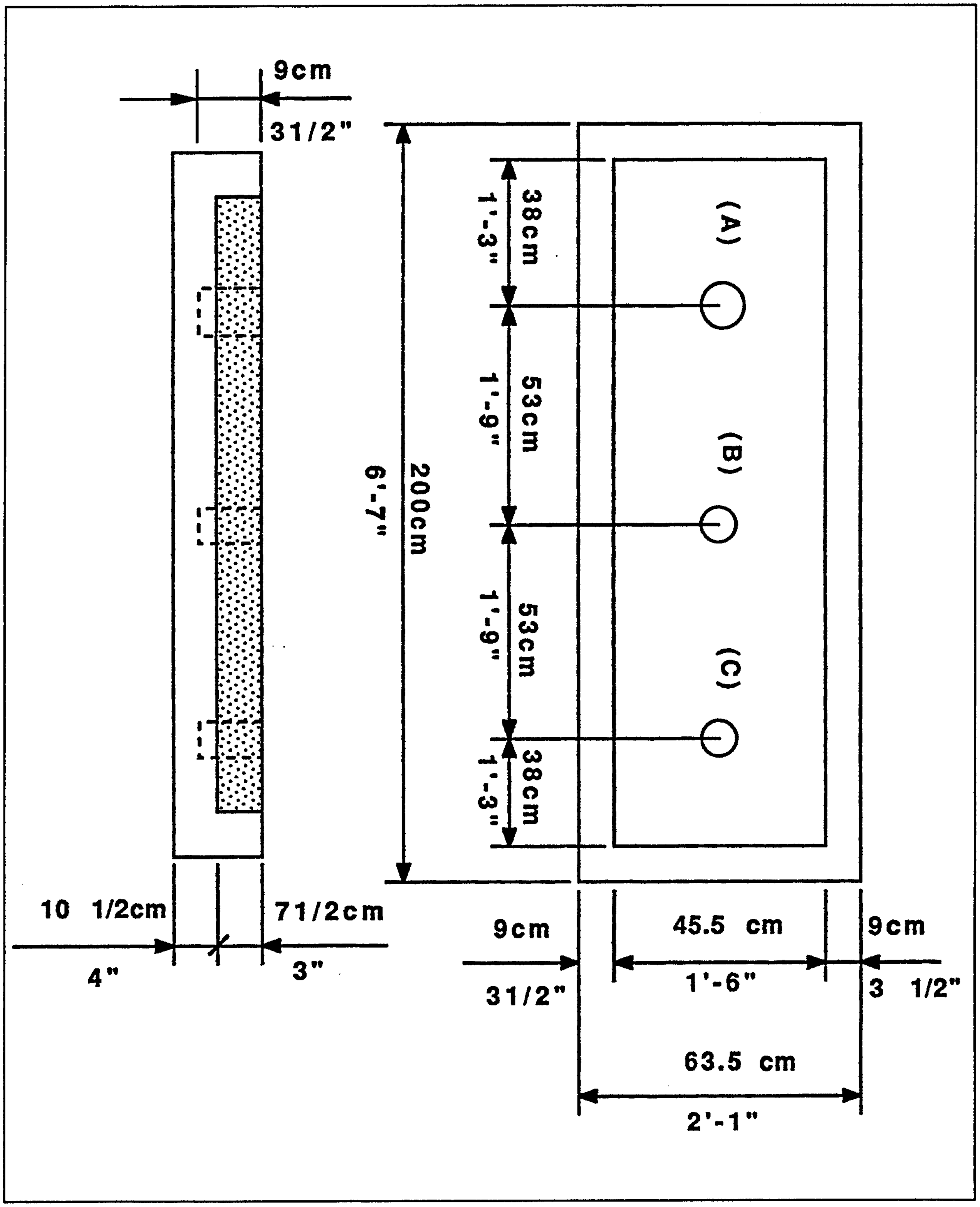


Figure 17. Location of 75-mm (3-in.) and 50-mm (2-in.) diam cores used for pull-off tests

Figure 18. Florida test site

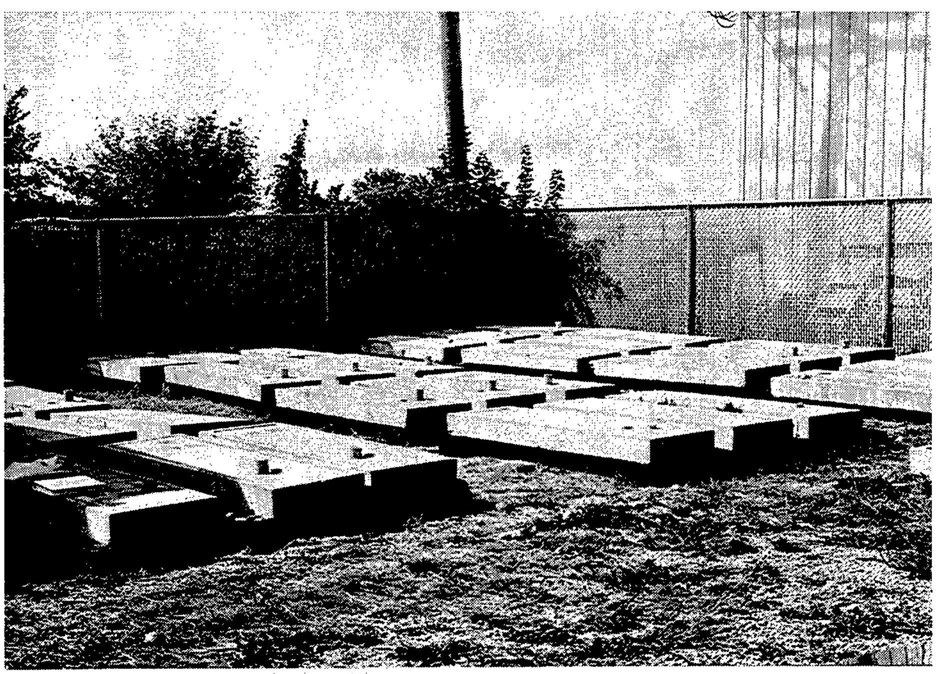


Figure 19. Illinois test site

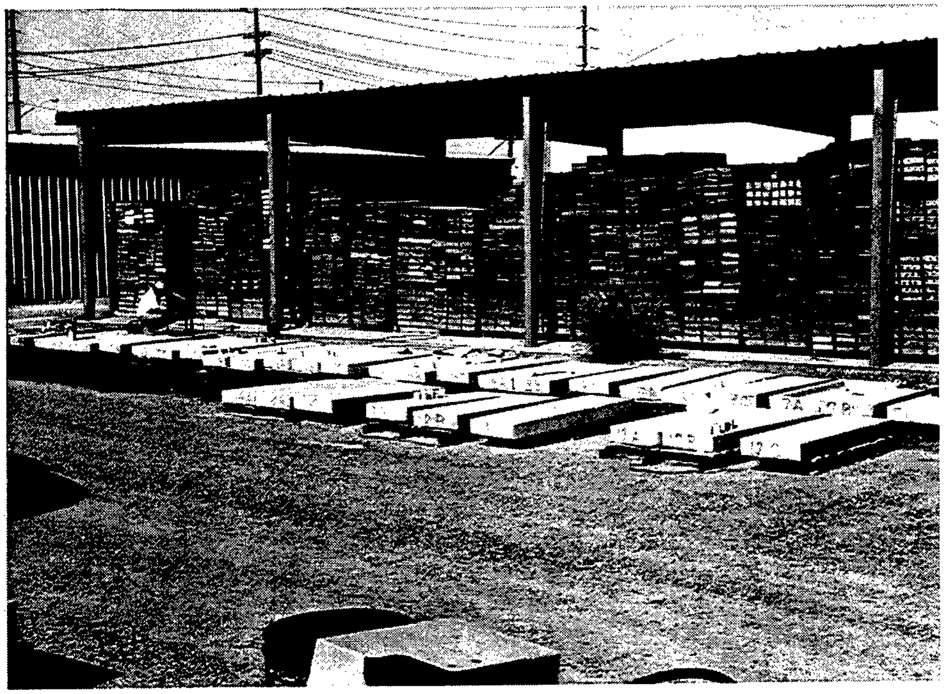


Figure 20. Arizona test site

Table 2
Pull-Off Strengths Determined with Germann Instruments Equipment (Florida)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	314	424	240	326	92.6	28.4	(I)	(S)	(I)
2	233	259	363	285	68.8	24.1	(I)	(E)	(I)
3	262	295	272	276	16.9	6.1	(R)	(R)	(R)
4	505	-	479	492	18.4	3.7	(S)	-	(S)
6	538	496	463	499	37.6	7.5	(S)	(S)	(S)
8	269	198	305	257	54.4	21.2	(R)	(I)	(R)
9	29	75	75	60	26.6	44.5	(I)	(I)	(I)
10	259	308	327	298	35.1	11.8	(S)	(I)	(S)
11	421	379	379	393	24.2	6.2	(R)	(I)	(I)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disc-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 3
Pull-Off Strengths Determined with Proceq DYNA Z15 Tester (Florida)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	254	281	225	253	28.0	11.1	(I)	(I)	(I)
2	295	261	331	296	35.0	11.8	(S)	(I)	(I)
3	240	254	225	240	14.5	6.1	(R)	(R)	(R)
4	451	429	422	434	15.1	3.5	(S)	(S)	(S)
6	451	415	429	432	18.1	4.2	(S)	(S)	(S)
8	225	211	261	232	25.8	11.1	(I)	(I)	(I)
9	63	91	77	77	14.0	18.2	(I)	(I)	(I)
10	274	254	274	267	11.5	4.3	(S)	(S)	(S)
11	429	379	408	405	25.1	6.2	(S)	(I)	(I)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(S) Repair material
(E) Disc-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 4
Pull-Off Strengths Determined with Modified Hilti Tester 4 (Florida)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	217	248	204	223	22.6	10.1	(R)	(R)	(R)
2	315	306	350	324	23.2	7.2	(I)	(S)	(S)
3	178	191	172	180	9.7	5.4	(R)	(R)	(R)
4	382	350	350	361	18.5	5.1	(S)	(I)	(S)
6	245	239	271	252	17.0	6.8	(S)	(S)	(S)
8	242	271	255	256	14.5	5.7	(R)	(R)	(S)
9	48	61	70	60	11.1	18.5	(I)	(I)	(I)
10	248	229	271	249	21.0	8.4	(S)	(S)	(S)
11	350	309	318	326	21.5	6.6	(I)	(S)	(S)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(T) Repair material
(E) Disc-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 5
Pull-Off Strengths Determined with Germann Instruments Equipment (Illinois)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	198	84	343	208	129.8	62.3	(R)	(I)	(I)
2	483	402	398	428	48.0	11.2	(S)	(S)	(S)
3	237	237	295	256	33.5	13.1	(R)	(R)	(R)
4	473	463	399	445	40.5	9.1	(S)	(S)	(S)
6	399	230	424	351	105.5	30.1	(S)	(E)	(S)
8	256	198	253	236	32.7	13.9	(R)	(I)	(R)
9	120	392	408	307	161.9	52.8	(R)	(R)	(I)
10	327	327	217	290	63.5	21.9	(S)	(S)	(S)
11	411	405	262	359	84.3	23.5	(I)	(I)	(R)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 6
Pull-Off Strengths Determined with Proceq DYNA Z15 Tester (Illinois)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	253	58*	218	236*	24.4*	10.4*	(S)	(I)	(I)
2	355	363	276	331	48.1	14.5	(S)	(S)	(S)
3	155	260	203	206	52.6	25.5	(R)	(R)	(R)
4	463	355	405	408	54.0	13.3	(R)	(S)	(S)
6	361	73**	405	383**	29.9**	7.8**	(S)	(S)	(S)
8	361	377	340	359	18.6	5.2	(I)	(E)	(I)
9	253	311	283	282	29.0	10.3	(R)	(R)	(S)
10	218	290	347	285	64.6	22.7	(S)	(S)	(S)
11	435	419	384	413	26.1	6.3	(R)	(R)	(I)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: * Disregard No. 1B because bond strength was significantly lower than other specimens.
** Disregard No. 6B because of significantly lower strength attributed to large voids along the failure plane.
1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 7
Pull-Off Strengths Determined with Modified Hilti Tester 4 (Illinois)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	204	-	185	195	13.4	6.9	(E)	-	(R)
2	191	191	172	185	11.0	5.9	(E)	(E)	(E)
3	153	102	127	127	25.5	20.0	(R)	(I)	(I)
4	255	242	248	248	6.5	2.6	(E)	(S)	(S)
6	191	166	223	193	28.6	14.8	(S)	(S)	(E)
8	140	159	140	146	11.0	7.5	(R)	(R)	(R)
9	248	197	185	210	33.5	15.9	(E)	(E)	(R)
10	255	191	255	234	37.0	15.8	(E)	(S)	(E)
11	159	-	210	185	36.1	19.5	(S)	-	(S)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 8
Pull-Off Strengths Determined with Germann Instruments Equipment (Arizona)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	-	217	309	263	65.1	24.7	-	(I)	(I)
2	324	405	275	335	65.7	19.6	(E)	(S)	(I)
3	204	314	301	273	60.1	22.0	(I)	(R)	(I)
4	156	84	149	130	39.7	30.6	(E)	(I)	(I)
6	113	311	217	214	99.0	46.4	(S)	(S)	(S)
8	282	334	275	297	32.2	10.9	(E)	(S)	(R)
9	211	272	353	279	71.2	25.6	(I)	(I)	(R)
10	308	136*	279	294	20.6*	7.0*	(S)	(S)	(S)
11	292	334	330	319	23.7	7.3	(S)	(S)	(S)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: * Disregard No. 10B because bond strength was significantly lower than other specimens.
1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 9
Pull-Off Strengths Determined with Proceq DYNA Z15 (Arizona)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	247	334	218	266	60.4	22.7	(E)	(I)	(S)
2	406	363	421	397	30.1	7.6	(S)	(S)	(S)
3	174	174	232	193	33.5	17.3	(I)	(R)	(R)
4	261	290	377	309	60.4	19.5	(S)	(S)	(S)
6	276	232	290	266	30.3	11.4	(S)	(I)	(S)
8	261	203	253	239	31.4	13.2	(I)	(I)	(I)
9	377	406	363	382	21.9	5.7	(S)	(S)	(I)
10	290	174	261	242	60.4	25.0	(S)	(S)	(S)
11	290	290	377	319	50.2	15.7	(S)	(S)	(S)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: 1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Table 10
Pull-Off Strengths Determined with Modified Hilti Tester 4 (Arizona)

Material Number	Pull-Off Strength, psi						Failure Mode		
	Repair Specimen			Average	Standard Deviation	Coefficient of Variation (COV)	Repair Specimen		
	A	B	C				A	B	C
1	159	159	191	170	18.5	10.9	(E)	(E)	(E)
2	350	287	318	318	31.5	9.9	(E)	(E)	(E)
3	159	175	213	182	27.7	15.2	(R)	(R)	(I)
4	287	223	223	244	37.0	15.1	(E)	(E)	(E)
6	178	64*	207	192*	20.2*	10.5*	(E)	(I)	(I)
8	191	197	223	204	17.0	8.4	(I)	(R)	(R)
9	255	255	287	266	18.5	7.0	(S)	(I)	(E)
10	191	210	191	197	11.0	5.6	(S)	(E)	(E)
11	247	247	287	260	23.1	8.9	(S)	(E)	(S)

Failure at:
(I) Interface between repair and substrate
(S) Substrate
(R) Repair material
(E) Disk-repair interface (epoxy)
Note: * Disregard No. 6B because bond strength was significantly lower than other specimens.
1,000 psi = 6.895 MPa; COV = (Standard deviation/Average) x 100

Figure 21. Failure at repair-substrate interface

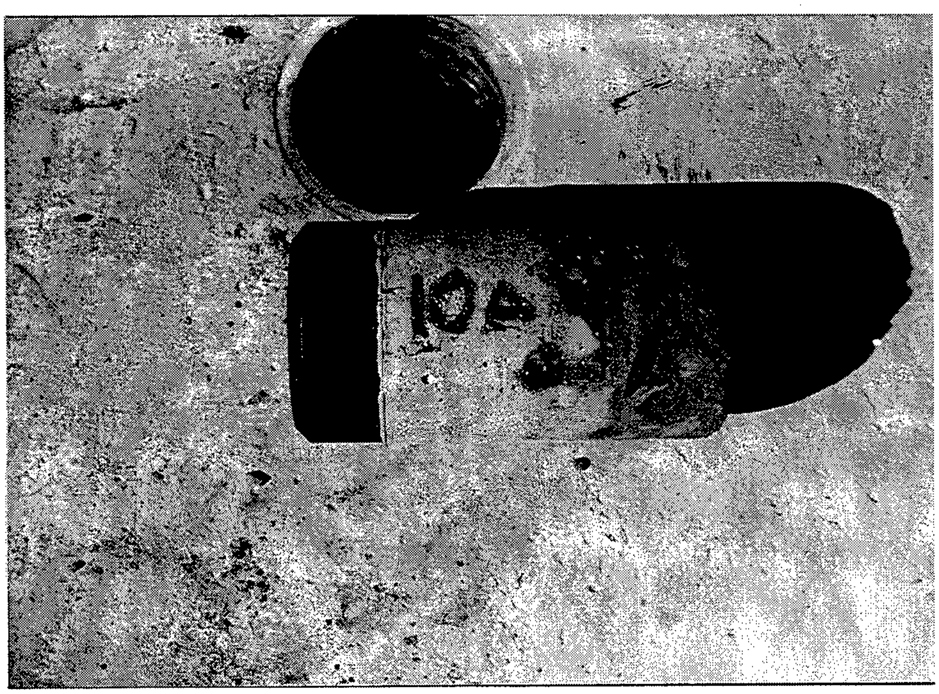


Figure 22. Failure in substrate concrete

Figure 23. Failure in repair material

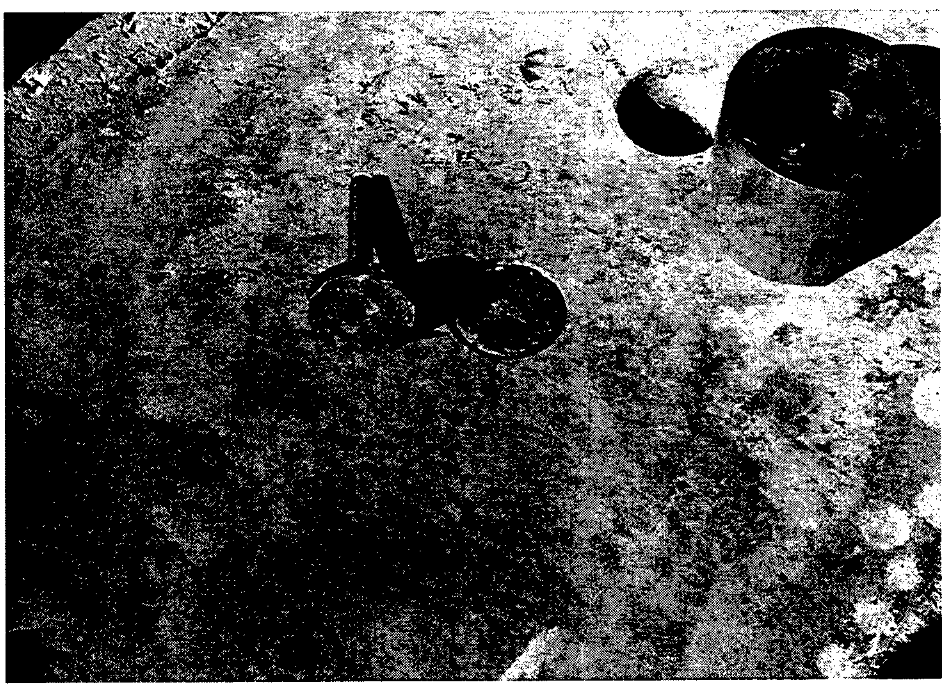


Figure 24. Failure at disc-repair interface

Two of the materials exhibited a relatively high number of failures in the repair. In 27 tests on Material No. 3, 21 failures (78 percent) occurred in the repair material. All failures in the repair material occurred at stresses significantly lower than the material's tensile strength of 3.5 MPa (513 psi) determined in laboratory tests. In 27 tests on Material No. 8, 13 failures (48 percent) occurred in the repair material. These failures in the repair material occurred at stresses significantly higher than the material's tensile strength of 1.5 MPa (215 psi) determined in laboratory tests.

Most of the materials exhibited a range of failure modes from full bond (adhesive) failure to full material failure (cohesive), be it in the concrete substrate or in the repair material. Three of the materials exhibited consistent failure modes when tested in Florida. In each test, Material Nos. 3, 6, and 9 failed in the repair material, concrete substrate, and the repair-substrate interface, respectively. With the exception of one test for each material, all failures for Material Nos. 4 and 10 were within the concrete substrate.

Material No. 2 exhibited consistent failures in the concrete substrate when tested with two types of equipment in Illinois. In contrast, all failures occurred at the steel disc-repair interface in tests with the Hilti tester. With the exception of two tests for each material, all failures for Material Nos. 4 and 6 were within the concrete substrate. Material No. 3 exhibited failure within the repair material in seven of nine Illinois tests.

Two materials exhibited the most consistent failure modes when tested in Arizona. The failure mode for Materials Nos. 10 and 11 was within the concrete substrate in seven of nine, and eight of nine tests, respectively.

Average pull-off strengths for the different failure modes are shown in Table 11.

Table 11
Comparison of Pull-Off Strengths with Different Failure Modes

	Average Strength, MPa (psi)		
Test Site	**Failure at Interface**	**Failure in Concrete Substrate**	**Failure in Repair Material**
Florida	1.57 (228)	2.34 (339)	1.73 (251)
Illinois	2.14 (310)	2.37 (344)	1.74 (253)
Arizona	1.62 (235)	2.10 (305)	1.61 (234)
Overall average	1.78 (258)	2.27 (329)	1.70 (246)

The analysis of the data presented in Table 11 indicates (a) that the overall mean tensile pull-off strength of the concrete substrate and bond at the interface is consistent across all test series and (b) that the overall mean failure strength of repair material is inconsistent with the materials' tensile strength, as tested in the laboratory. This can be explained by the fact that pull-off tensile strength depends not only on material properties but also on in situ fabrication techniques.

The overall average pull-off strength for each material as an average of strengths measured by three testing devices in Florida, Illinois, and Arizona is presented in Tables 12-14, and the overall summary is presented in Table 15. Since the Germann Instrument's pull-off apparatus is assumed to be the most precise, the bond strengths determined with DYNA Z15 and Hilti are compared with the results of tests with the Germann Instruments apparatus.

Table 12
Average Pull-Off Strength (Florida)

Material Number	Average Pull-Off Strength, psi			Strength Ratio		Average Pull-Off Strength, psi
	Germann Instruments	Proceq	Hilti	Germann / Proceq	Germann / Hilti	
1	326	253	223	1.29	1.46	267
2	285	296	324	0.96	0.88	302
3	276	240	180	1.15	1.53	232
4	492	434	361	1.14	1.36	429
6	499	432	252	1.16	1.98	394
8	257	232	256	1.11	1.00	248
9	60	77	60	0.78	1.00	66
10	298	267	249	1.12	1.20	271
11	393	405	326	0.97	1.21	375
Average				1.08	1.29	

Note: 1,000 psi = 6.895 MPa.

Table 13
Average Pull-off Strength (Illinois)

Material Number	Average Pull-Off Strength, psi			Strength Ratio		Average Pull-Off Strength, psi
	Germann Instruments	Proceq	Hilti	Germann / Proceq	Germann / Hilti	
1	208	236	195	0.88	1.07	213
2	428	331	185	1.29	2.31	315
3	256	206	127	1.24	2.01	196
4	445	408	248	1.09	1.79	367
6	351	383	193	0.92	1.82	309
8	236	359	146	0.66	1.62	247
9	307	282	210	1.09	1.46	266
10	290	285	234	1.02	1.24	270
11	359	413	185	0.87	1.96	319
Average				1.01	1.70	

Note: 1,000 psi = 6.895 MPa.

Table 14
Average Pull-Off Strength (Arizona)

Material Number	Average Pull-Off Strength, psi			Strength Ratio		Average Pull-Off Strength, psi
	Germann Instruments	Proceq	Hilti	Germann / Proceq	Germann / Hilti	
1	263	266	170	0.99	1.55	233
2	335	397	318	0.84	1.05	350
3	273	193	182	1.41	1.50	216
4	130	309	244	0.42	0.53	228
6	214	266	192	0.80	1.11	224
8	297	239	204	1.24	1.46	247
9	279	382	266	0.73	1.05	309
10	294	242	197	1.21	1.49	244
11	319	319	260	1.00	1.23	299
Average				0.96	1.22	

Note: 1,000 psi = 6.895 MPa.

Table 15
Summary of Pull-Off Strength of Experimental Repairs

Testing Site	Average Pull-Off Strength MPa, psi								
	Material								
	1	2	3	4	6	8	9	10	11
Florida	1.85 (267)	2.07 (302)	1.60 (232)	2.96 (429)	2.72 (394)	1.71 (248)	0.46* (66)*	1.87 (271)	2.58 (375)
Illinois	1.47 (213)	2.17 (315)	1.35 (196)	2.45 (367)	2.13 (309)	1.70 (247)	1.83 (266)	1.86 (270)	2.20 (319)
Arizona	1.61 (233)	2.41 (350)	1.49 (216)	1.57 (228)	1.54 (224)	1.70 (247)	2.13 (309)	1.68 (244)	2.06 (299)
Overall (3 sites)	1.64 (238)	2.22 (322)	1.48 (215)	2.33 (341)	2.13 (309)	1.70 (247)	1.99 (288)	1.81 (262)	2.28 (331)
COV, %	11.5	7.7	8.4	30.2	27.5	0.2	10.6	5.8	11.9

Note: * Disregard because the results are significantly different from the others.

The effect of the environment on the pull-off strength of experimental repairs is presented in Figure 25.

The analysis of the test results indicates that exposure conditions did not affect the failure mode, nor did the exposure conditions affect the pull-off strength which is to be expected, because the majority of failures occurred in the concrete substrate.

As can be seen from the overall analysis of pull-off tensile strength results, the test data were highly variable; however, the average pull-off strength data presented in Table 15 shows that trends in consistency can be discussed with confidence.

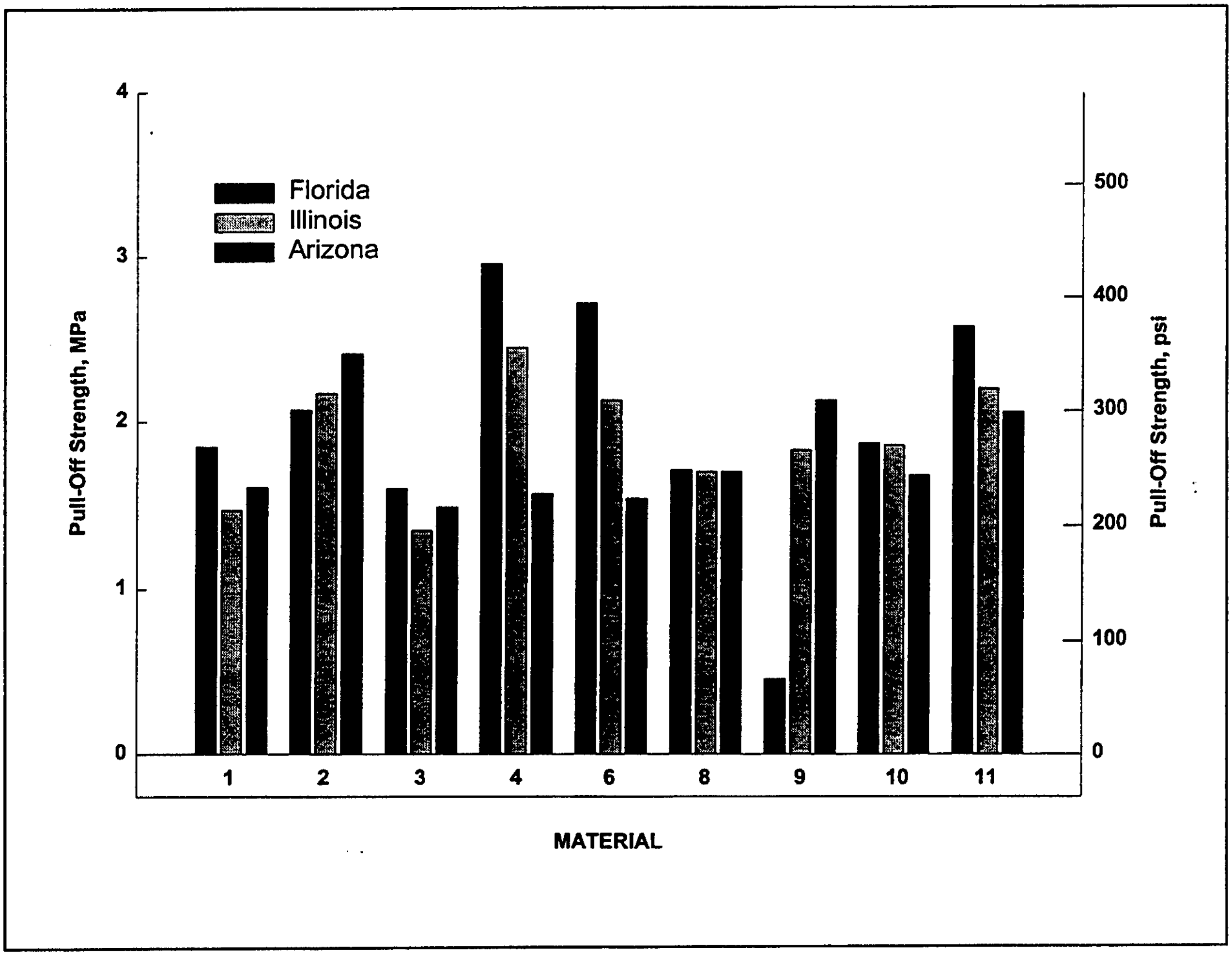


Figure 25. Effect of environment on pull-off strength of experimental repairs

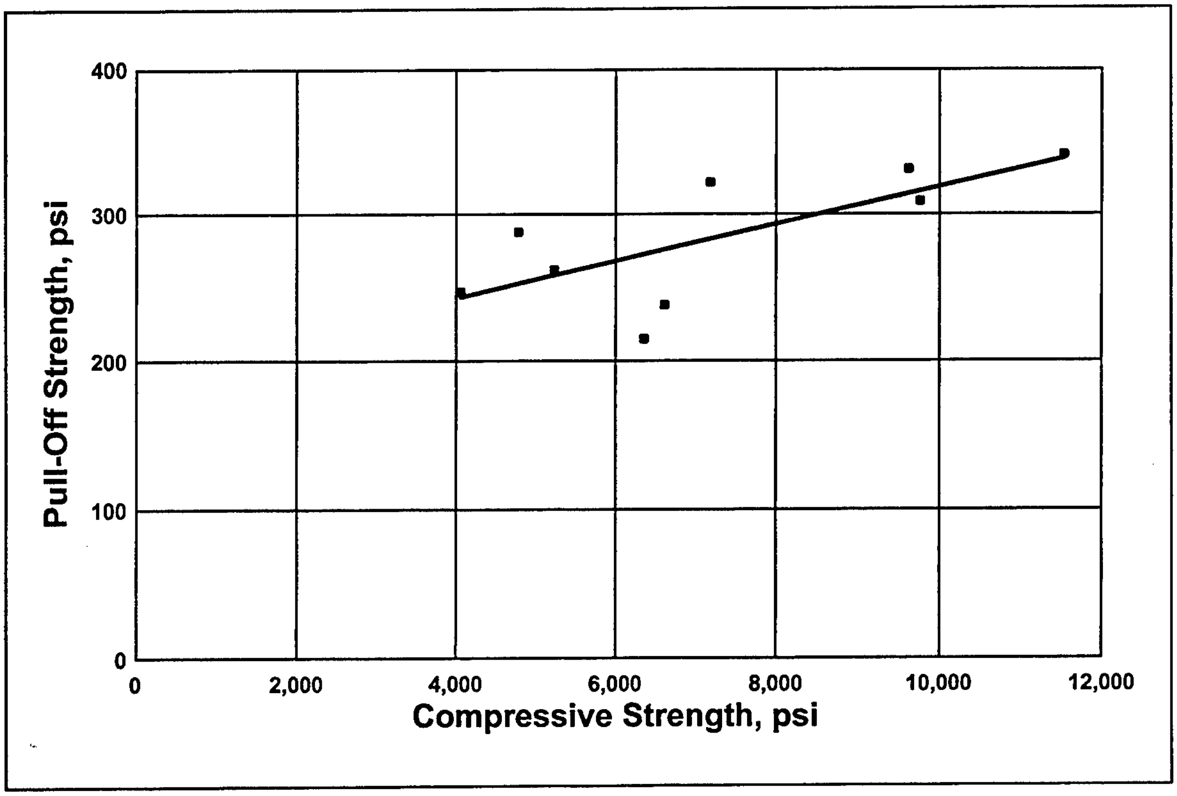
The average pull-off strengths for all test sites ranged from 1.5 to 2.3 MPa (215 to 341 psi) with an overall average strength of 2.0 MPa (284 psi). Four materials (Nos. 2, 4, 6, 11) exhibited an average tensile bond strength in excess of 2.1 MPa (300 psi).

Polymer-modified cementitious materials had an average pull-off strength of 1.8 MPa (260 psi) compared with 2.1 MPa (304 psi) for cementitious repair materials. One possible explanation for the stronger bond of cementitious materials is to assume that the surfaces of the substrate concrete and cementitious repair material in contact with it were strengthened by penetration of epoxy into the pores of the substrate and into the fresh repair material. This penetration would strengthen both materials along their interface. In contrast, the polymer-modified repair materials probably did not allow the epoxy to penetrate into its pore system to the same degree. Another possible factor is that compaction problems existed when dealing with some of the polymer-modified cementitious materials.

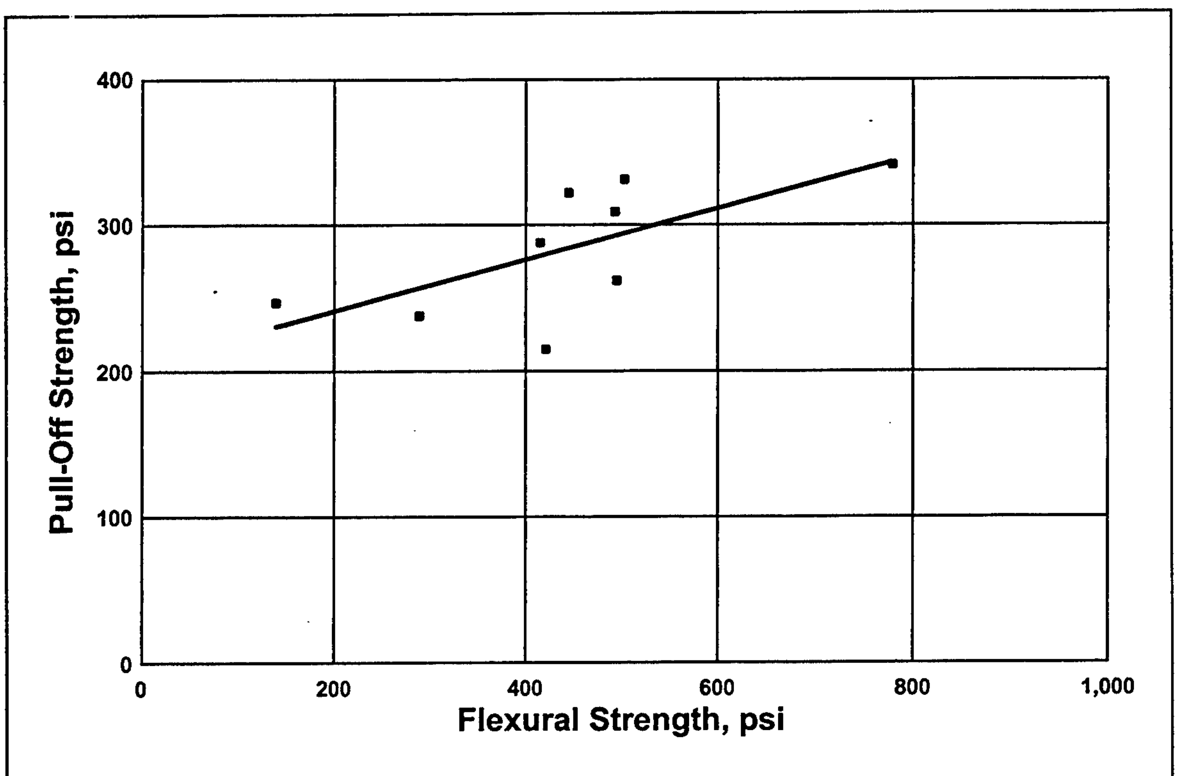
It is generally agreed that the magnitude and rate of strength gain in concrete and other cementitious materials usually do not apply to the interface bond strength; high strength in the repair material does not necessarily indicate a high

bond strength. However, results of this study indicate that there was a general correlation between higher compressive and flexural strengths, as determined in the laboratory, and increased pull-off strengths in field tests (Figure 26). In contrast, the overall trend was for decreased pull-off strengths with increased tensile strength. Excluding one material (No. 3), there was a significant correlation between the results of laboratory tensile tests and field pull-off tests (Figure 27).

Results of the tensile pull-off tests should be viewed as an indication of the relative bond strength between the various repair materials and the substrate concrete. Obviously, the occurrence of mixed failure modes instead of 100 percent bond failures makes the determination of the true bond strength impossible. In the case of mixed failure modes, an overall average of the test results tends to underestimate the actual bond strength of the repair system.



a. Compressive strength



b. Flexural strength

Figure 26. Correlation between results of laboratory strength tests and field pull-off tests

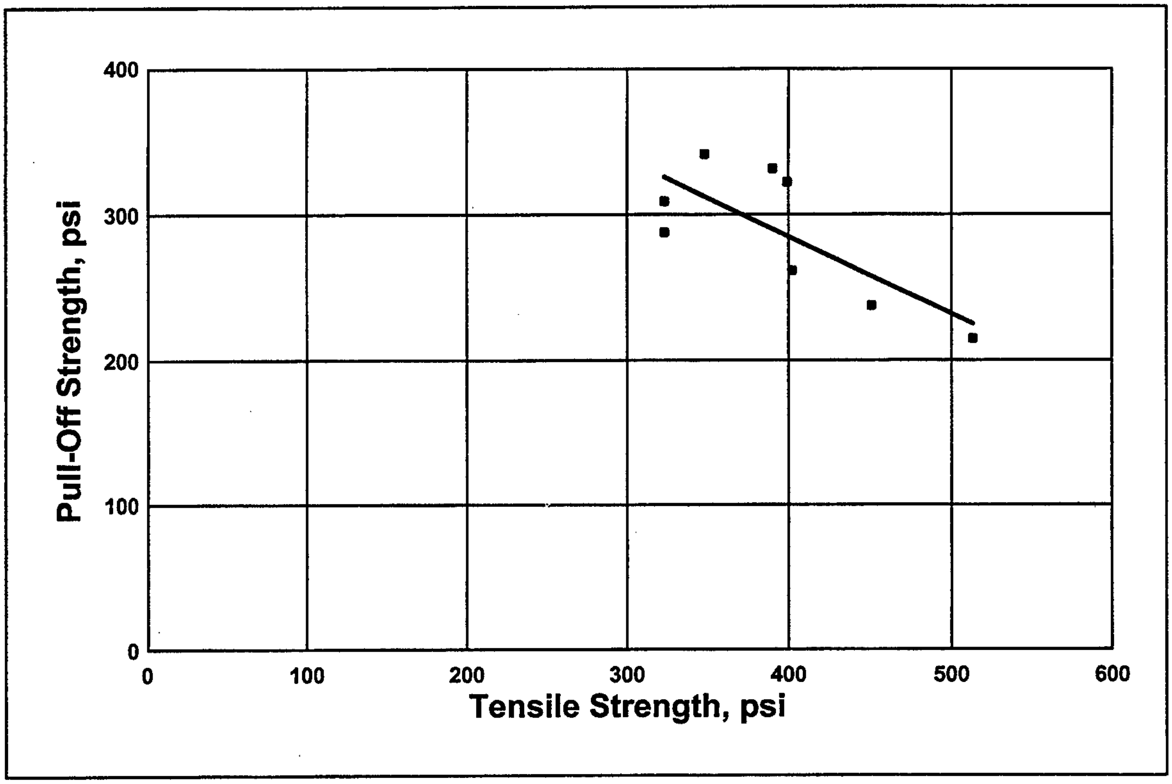


Figure 27. Correlation between results of laboratory tensile strength tests and field pull-off tests

3 Relative Performance of Three Testing Devices

In addition to developing data on the bond properties for nine repair materials, the scope of the study required the determination of which testing equipment produced the most reliable, most consistent results as well as which equipment is the most practical for in situ use. Since one of the specified tasks in this study was to recommend a reliable and easy-to-use field device for determining pull-off strength as part of the quality assurance program, the individual devices—Germann Instruments (GI) Bond Test, Proceq DYNA Z15, and Hilti Tester 4 (Modified)—were compared against each other on the same repair materials used for the experimental repair field slabs. Data consistency, ease of use, and other details on each test device are discussed in this chapter.

The analysis of the COV of three repair specimens for each repair material presented in Tables 16-18 shows that it varies: for the GI from 3.7 to 62.3 percent, for Proceq from 3.5 to 25.5 percent, and for Hilti from 2.6 to 20.0 percent. The smallest COV between specimens of the same material as measured by the Hilti device can be explained by the assumption that the Hilti tester was not sensitive to differences in the pull-off strength. It should be noted that it was considered inappropriate to use the standard deviation to analyze the precision because of the large differences in the averages and standard deviations of the different test equipment for a given repair material. It was considered to be more appropriate to use COV as a measure of relative precision, because COV is a measure of precision adjusted for the magnitude of average.

The average pull-off strength for the repair materials as measured by each testing device in Florida, Illinois, and Arizona is presented in Figures 28-30. The summary of the performance analysis for each testing device is presented in Table 19 and Figure 31.

The Germann Instruments (GI) testing equipment is considered to be the most reliable of the three devices investigated because of its higher overall average failure pull-off stress and better relative precision (Table 19). It is believed that the higher average failure stress is the result of less eccentricity being introduced by this apparatus as compared with other test apparatus. The better relative precision (lowest overall average COV) is attributed to the controlled loading rate.

Table 16
Summary of Pull-Off Test Data (Florida)

Material	Average Pull-Off Strength, MPa (psi)			Standard Deviation, MPa (psi)			Coefficient of Variation, %		
	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)
1	2.25 (326)	1.74 (253)	1.54 (223)	0.64 (92.6)	0.19 (28.0)	0.16 (22.6)	28.4	11.1	10.1
2	1.97 (285)	2.04 (296)	2.23 (324)	0.47 (68.8)	0.24 (35.0)	0.16 (23.2)	24.1	11.8	7.2
3	1.90 (276)	1.65 (240)	1.24 (180)	0.12 (16.9)	0.10 (14.5)	0.07 (9.7)	6.1	6.1	5.4
4	3.39 (492)	2.99 (434)	2.49 (361)	0.13 (18.4)	0.10 (15.1)	0.13 (18.5)	3.7	3.5	5.1
6	3.44 (499)	2.98 (432)	1.74 (252)	0.26 (37.6)	0.12 (18.1)	0.12 (17.0)	7.5	4.2	6.8
8	1.77 (257)	1.60 (232)	1.77 (256)	0.38 (54.4)	0.18 (25.8)	0.10 (14.5)	21.2	11.1	5.7
9	0.41 (60)	0.53 (77)	0.41 (60)	0.18 (26.6)	0.10 (14.0)	0.08 (11.1)	44.5	18.2	18.5
10	2.05 (298)	1.84 (267)	1.72 (249)	0.24 (35.1)	0.08 (11.5)	0.14 (21.0)	11.8	4.3	8.4
11	2.71 (393)	2.79 (405)	2.25 (326)	0.17 (24.2)	0.17 (25.1)	0.15 (21.5)	6.2	6.2	6.6
Average				0.29 (41.6)	0.14 (20.8)	0.12 (17.7)	17.1	8.5	8.2

Table 17
Summary of Pull-Off Test Data (Illinois)

Material	Average Pull-Off Strength, MPa (psi)			Standard Deviation, MPa (psi)			Coefficient of Variation, %		
	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)
1	1.43 (208)	1.63 (236)	1.34 (195)	0.89 (129.8)	0.17 (24.4)	0.09 (13.4)	62.3	10.4	6.9
2	2.95 (428)	2.28 (331)	1.27 (185)	0.33 (48.0)	0.33 (48.1)	0.08 (11.0)	11.2	14.5	5.9
3	1.76 (256)	1.42 (206)	0.88 (127)	0.23 (33.5)	0.36 (52.6)	0.18 (25.5)	13.1	25.5	20.0
4	3.07 (445)	2.81 (408)	1.71 (248)	0.28 (40.5)	0.37 (54.0)	0.04 (6.5)	9.1	13.3	2.6
6	2.42 (351)	2.64 (383)	1.33 (193)	0.73 (105.5)	0.21 (29.9)	0.20 (28.6)	30.1	7.8	14.8
8	1.63 (236)	2.48 (359)	1.01 (146)	0.23 (32.7)	0.13 (18.6)	0.08 (11.0)	13.9	5.2	7.5
9	2.11 (307)	1.95 (282)	1.45 (210)	1.12 (161.9)	0.20 (29.0)	0.23 (33.7)	52.8	10.3	15.9
10	2.00 (290)	1.96 (285)	1.61 (234)	0.44 (63.5)	0.45 (64.6)	0.26 (37.0)	21.9	22.7	15.8
11	2.48 (359)	2.85 (413)	1.27 (185)	0.58 (84.3)	0.18 (26.1)	0.25 (36.1)	23.5	6.3	19.5
Average				0.54 (77.7)	0.27 (38.6)	0.16 (22.5)	26.4	12.9	12.1

Table 18
Summary of Pull-Off Test Data (Arizona)

Material	Average Pull-Off Strength, MPa (psi)			Standard Deviation, MPa (psi)			Coefficient of Variation, %		
	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)	Germann Instruments Bond-Test	Proceq DYNA Z15	Hilti Tester 4 (Modified)
1	1.81 (263)	1.83 (266)	1.17 (170)	0.45 (65.1)	0.42 (60.4)	0.13 (18.5)	24.7	22.7	10.9
2	2.31 (335)	2.74 (397)	2.19 (318)	0.45 (65.7)	0.21 (30.1)	0.22 (31.5)	19.6	7.6	9.9
3	1.88 (273)	1.33 (193)	1.25 (182)	0.42 (60.1)	0.23 (33.5)	0.19 (27.7)	22.0	17.3	15.2
4	0.90 (130)	2.13 (309)	1.68 (244)	0.27 (39.7)	0.42 (60.4)	0.26 (37.0)	30.6	19.5	15.1
6	1.48 (214)	1.83 (266)	1.32 (192)	0.68 (99.0)	0.21 (30.3)	0.14 (20.2)	46.4	11.4	10.5
8	2.05 (297)	1.65 (239)	1.41 (204)	0.22 (32.2)	0.22 (31.4)	0.12 (17.0)	10.9	13.2	8.4
9	1.92 (279)	2.63 (382)	1.83 (266)	0.49 (71.2)	0.16 (21.9)	0.15 (18.5)	25.6	5.7	7.0
10	2.03 (294)	1.67 (242)	1.36 (197)	0.64 (20.6)	0.42 (60.4)	0.07 (11.0)	7.0	25.0	5.6
11	2.20 (319)	2.20 (319)	1.79 (260)	0.16 (23.7)	0.35 (50.2)	0.15 (23.1)	7.3	15.7	8.9
Average				0.37 (53.0)	0.29 (42.1)	0.16 (22.7)	21.6	15.3	10.2

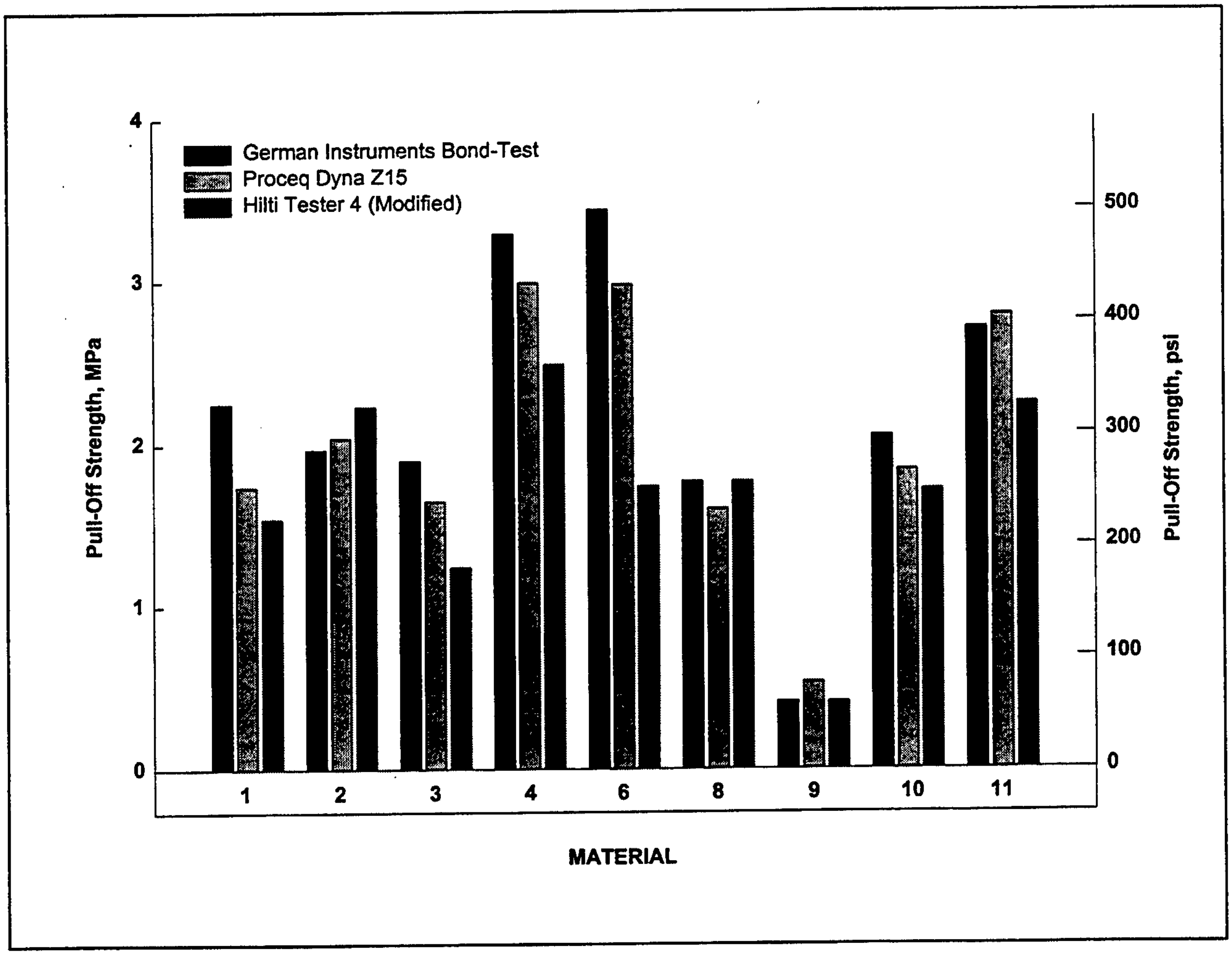


Figure 28. Effect of apparatus on pull-off strength of experimental repairs in Florida

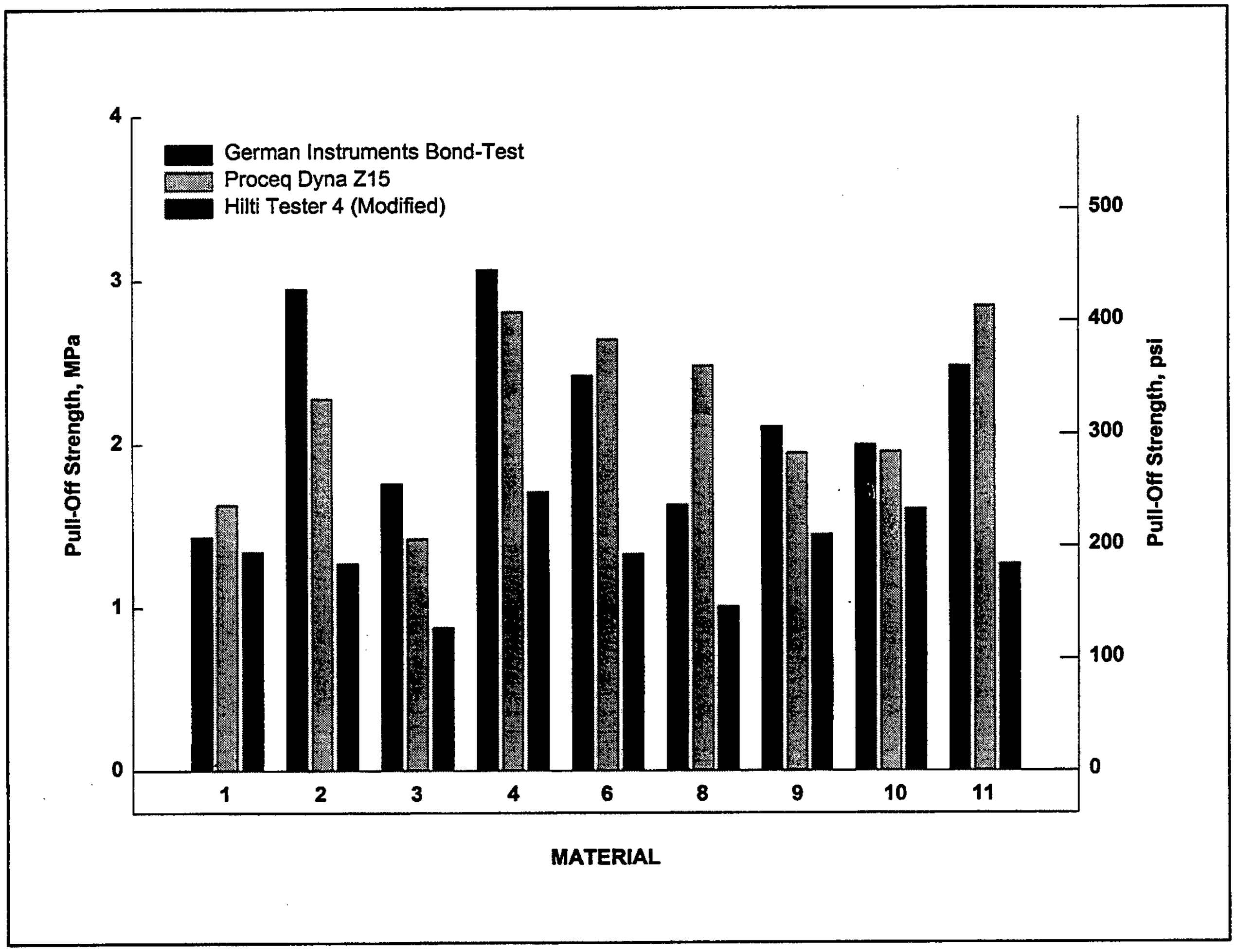


Figure 29. Effect of apparatus on pull-off strength of experimental repairs in Illinois

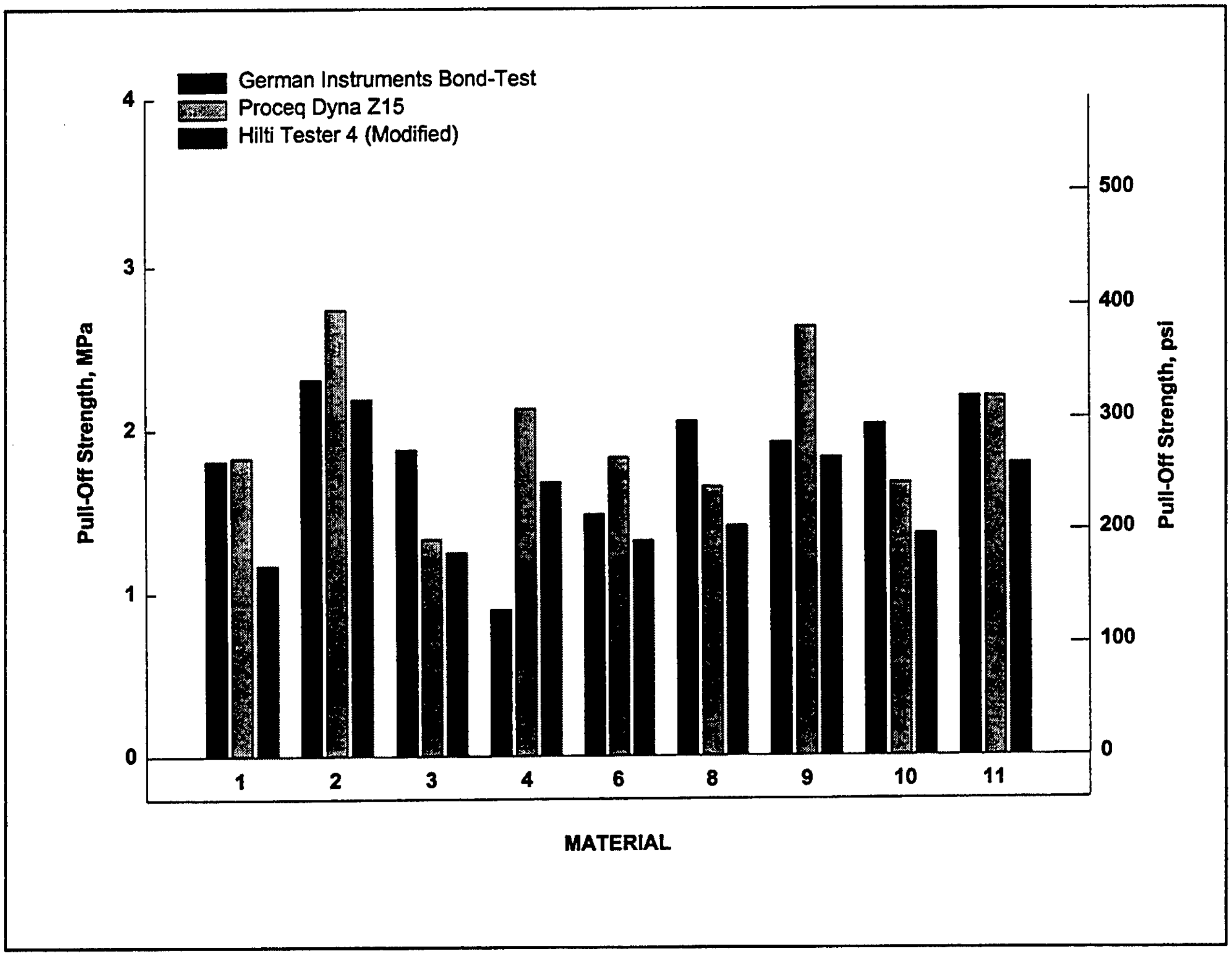


Figure 30. Effect of apparatus on pull-off strength of experimental repairs in Arizona

Table 19

Summary of Average Strength and Coefficient of Variation Values for Three Testing Devices

Repair Material No.	Pull-Off Test Device														
	Germann Instruments Bond Test					Proceq DYNA Z15					Hilti Tester 4 (Modified)				
	Pull-Off Strength, psi				COV, %	Pull-Off Strength, psi				COV, %	Pull-Off Strength, psi				COV, %
	FL	IL	AZ	Avg		FL	IL	AZ	Avg		FL	IL	AZ	Avg	
1	326	208	263	286	22	253	236	266	252	6	223	195	170	196	14
2	285	428	335	349	21	296	331	397	341	15	324	185	318	276	29
3	276	256	273	269	4	240	206	193	213	11	180	127	182	163	19
4	492	445	130**	468	7	434	408	309	384	17	361	248	244	284	23
6	499	351	214	355	40	432	383	266	360	24	252	193	192	212	16
8	257	236	297	263	12	232	359	239	277	26	256	146	204	202	27
9	60**	307	279	293	7	77**	282	382	332	21	60**	210	266	238	17
10	298	290	294	294	1	267	285	242	265	8	249	234	197	227	12
11	393	359	319	357	10	405	413	319	379	14	326	185	260	257	27
Overall Average				326	14				311	16				228	20

Note: 1,000 psi = 6.895 MPa.
Coefficient of Variation (COV) = (Standard deviation/Average) x 100.
** Disregard because the results are significantly lower than the others.

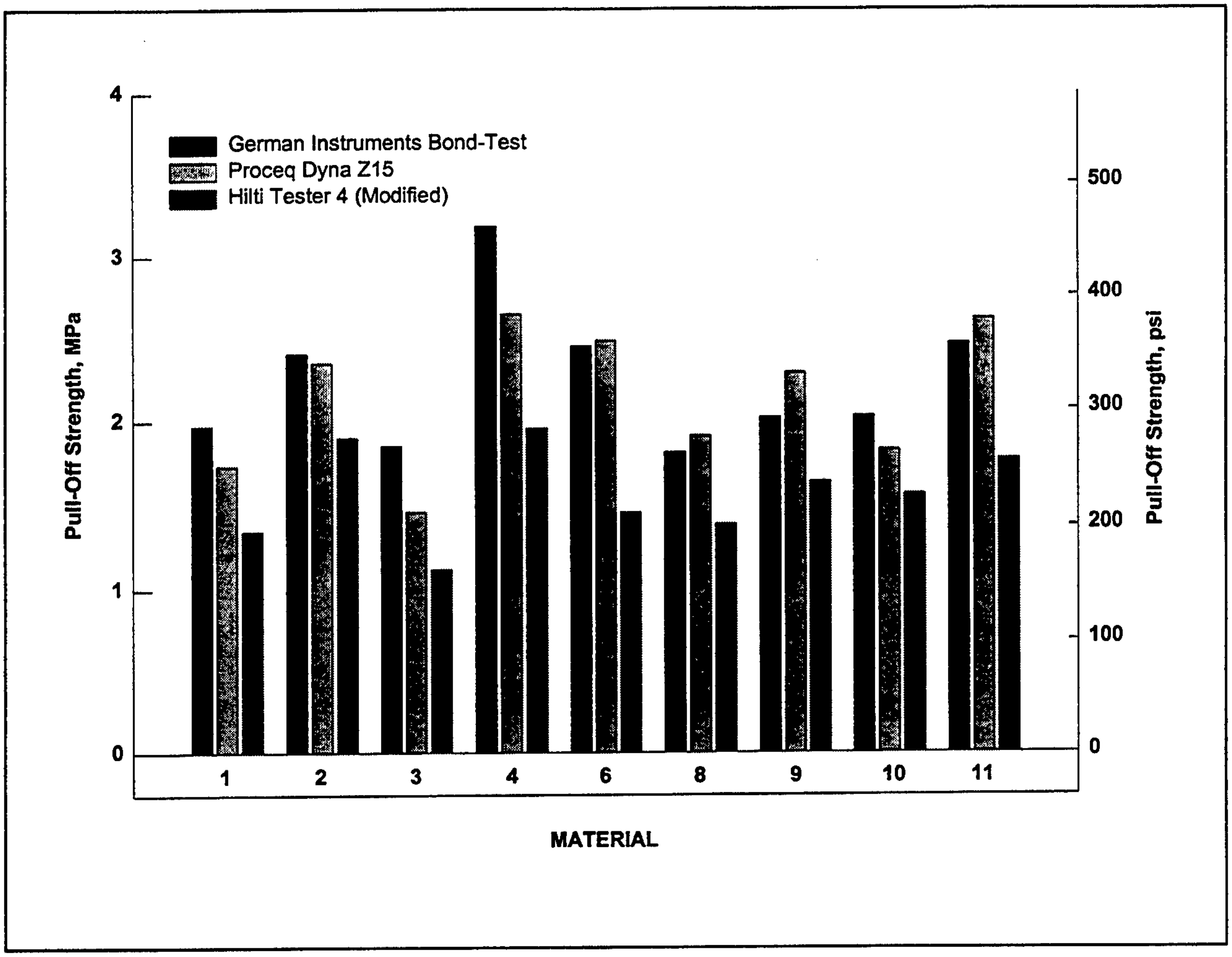


Figure 31. Average of pull-off strengths of experimental repairs tested by different apparatuses at three testing sites

Because the GI test results are relatively more precise and consistent, these test results are used as standards against which the other devices are compared (strength ratios in Tables 12-14).

The pull-off test results summarized in Table 19 show that the overall average COV for the GI equipment was 14 percent. Excluding Material No. 6, the maximum COV was 22 percent and the overall average was 10.5 percent. In comparison, the overall average COV for the Proceq and Hilti equipment was 16 and 20 percent, respectively. The maximum COV for the Proceq and Hilti equipment was 26 and 29 percent, respectively. The analysis of COV values indicates that the results obtained with all three testing devices can be described as variable and very variable.

The analysis based on pull-off strength and COV of repairs with nine materials as tested by the three devices demonstrated the following:

a. The results obtained with the Germann Instruments test equipment are judged to be comparable with the Proceq device because of the following:

(1) The average pull-off strengths were not substantially different from a practical viewpoint. Overall for the three test sites, the pull-off strengths obtained with the GI equipment averaged only 1.02 times higher than strengths obtained with the Proceq equipment (Tables 12-14). With three exceptions (Material No. 8 in Illinois, and Material Nos. 3 and 4 in Arizona), the strength ratios were within the range of 0.73 to 1.29.

(2) Overall, the average COV was essentially the same for the GI and Proceq equipment, 14 and 16 percent, respectively. Thus the precision (or absence of precision) of the two devices can be considered comparable.

b. The results obtained with the Hilti tester are judged to be incomparable with the GI equipment because the average pull-off strengths were substantially different.

(1) Overall for the three test sites, the pull-off strengths obtained with the GI equipment averaged 1.40 times higher than strengths obtained with the Hilti equipment (Tables 12-14). With only two exceptions (Material No. 2 in Florida and Material No. 4 in Arizona), average pull-off strengths obtained with the GI equipment were equal to or higher than strengths obtained with the Hilti equipment with a maximum ratio of 2.31.

(2) The COV for the Hilti equipment ranged from 12 to 29 percent with an overall average of 20 percent. In comparison, the overall average COV for the GI equipment was 14 percent. Excluding Material No. 6, the maximum COV for the GI equipment was 22 percent and the overall average was 10.5 percent. Based on these substantial differences, the precision of these two devices is considered to be incomparable.

Controlling the eccentricity of the applied load in a core pull-off test is one of the critical factors affecting the test results. Load eccentricity depends on the normality of the drilling relative to the substrate and accuracy of positioning the metal disc on top of the core. Load eccentricity leads to a very substantial increase in maximum stress at the core periphery. The study demonstrated that only Germann Instrument equipment allows for properly controlled normality of the drilling to the repair surface and positioning of the steel disc. However, the difficulty still lies in keeping the core's substrate-repair interface perpendicular to the tensile force.

The rate of loading is another critical factor in pull-off testing affecting test results. Higher rates generally result in higher failure loads. The Germann Instruments pull-off tester has an automatically controlled steady load application rate of 0.02 MPa per second, which compares with 0.05 ± 0.01 MPa per second recommended by the European standard.

No information has been found on the rate of loading for the Proceq testing device. The generally good correlation between Proceq and Germann Instruments would indicate that Proceq also has a steady rate of similar magnitude. The Hilti tester has no capacity for controlling load application, and the results are, to a large degree, dependent on the operator. Also, it was difficult to accurately determine the ultimate applied load because of the small size of the gauge and absence of any needle indicator for maximum load. Site testing clearly demonstrated certain difficulties of conducting properly controlled tests with the Hilti tester.

Another issue concerning the different testers is their ease of in situ use. It should be concluded that ease of use, as a parameter for comparing the different bond test equipment, is a relative term since none of the equipment and procedures involved are particularly easy to use. However, the Proceq and Hilti equipment were much easier to use compared with that of Germann Instruments.

Germann Instruments Bond-Test equipment consists of four cases with different kits consisting of a variety of features, which makes it very questionable as to the practicality of its day-to-day use in the field. The high cost of the equipment is another issue that limits its use by contractors for quality control purposes. However, it has unquestionable advantages when used by a specialized testing agency and operated by a specialized technician.

4 Influence of Partial Core Depth on Results of Pull-Off Bond Strength

The pull-off test method, when used to test the bond strength between repair material and substrate concrete, is subject to several important practical aspects that can significantly influence the accuracy of the test results. These factors include stiffness of the metal disc used for testing, rate of load increase, modulus of elasticity of repair material and substrate concrete, and drilling depth of the partial core into the substrate concrete. Theoretical studies and field experimental tests were conducted to examine the influence of the depth of partial core drilling into the substrate on the results of the pull-off tests and to develop recommendations to increase the accuracy and consistency of testing. Three repair materials (No. 2, 6, and 10) were selected for this part of the testing program.

Field Experimental Program

For this test series, the only variable for each repair system was the depth of the core drilling below the bond line. Germann Instruments Bond-Test equipment was used for drilling and testing. Three experimental repairs were used for each material, and three 75-mm (3-in.) diam partial depth cores were drilled below the bond interface in each specimen: 13 mm (0.5 in.), 25 mm (1 in.), and 38 mm (1.05 in.) into the substrate concrete.

The experimental determination of pull-off strengths was conducted on field repairs located in Phoenix, AZ. The ultimate tensile stresses and mode of failure are summarized in Table 20. Partially cored pull-off strength values were correlated against theoretical values.

Theoretical Studies

The theoretical analysis was based on the idealized assumption of a linear isotropic solid model. The 27 partial cores tested were modeled in finite elements using STAAD III Software. All specimens were modeled in a two-dimensional, 6.35-mm (0.25-in.) thick slice along the specimen (Figure 32). The model consists

Table 20
Results of Pull-Off Strength Tests of Experimental Repairs with Different Core Depths

Material	Repair Specimen	Core Depths, mm (in.)					
		89 (3.5)		102 (4.0)		114 (4.5)	
		Failure Stress MPa (psi)	Mode of Failure	Failure Stress MPa (psi)	Mode of Failure	Failure Stress MPa (psi)	Mode of Failure
2	2A	2.26 (324)	Disk-repair interface	2.05 (295)	13 mm (½ in.) in substrate concrete	1.27 (181)	19 mm (¾ in.) in substrate concrete
	2B	2.82 (405)	3 mm (1/8 in.) in substrate concrete	1.65 (237)	2 mm (1/16 in.) in substrate concrete	1.47 (212)	2 mm (1/16 in.) in substrate concrete
	2C	1.92 (275)	Interface between repair and substrate	2.75 (396)	Disk-repair interface	2.26 (324)	13 mm (½ in.) in substrate concrete
6	6A	0.80 (113)	Surface of substrate concrete	1.72 (246)	19 mm (¾ in.) in substrate concrete	1.77 (253)	Surface of substrate concrete
	6B	2.17 (311)	6 mm (¼ in.) in substrate concrete	1.94 (278)	Disk-repair interface	1.61 (230)	From 0 to 13 mm (½ in.) in substrate concrete
	6C	1.52 (218)	6 mm (¼ in.) in substrate concrete	2.17 (311)	Interface between repair and substrate	1.52 (218)	Surface of substrate concrete
10	10A	2.14 (308)	6 mm (¼ in.) in substrate concrete	1.07 (153)	Disk-repair interface	1.77 (253)	32 mm (1-¼ in.) in substrate concrete
	10B	0.96 (137)	Surface of substrate concrete	1.74 (245)	13 mm (½ in.) in substrate concrete	1.94 (278)	25 mm (1 in.) in substrate concrete
	10C	1.94 (278)	Surface of substrate concrete	1.03 (145)	Disk-repair interface	2.23 (321)	Surface of substrate concrete

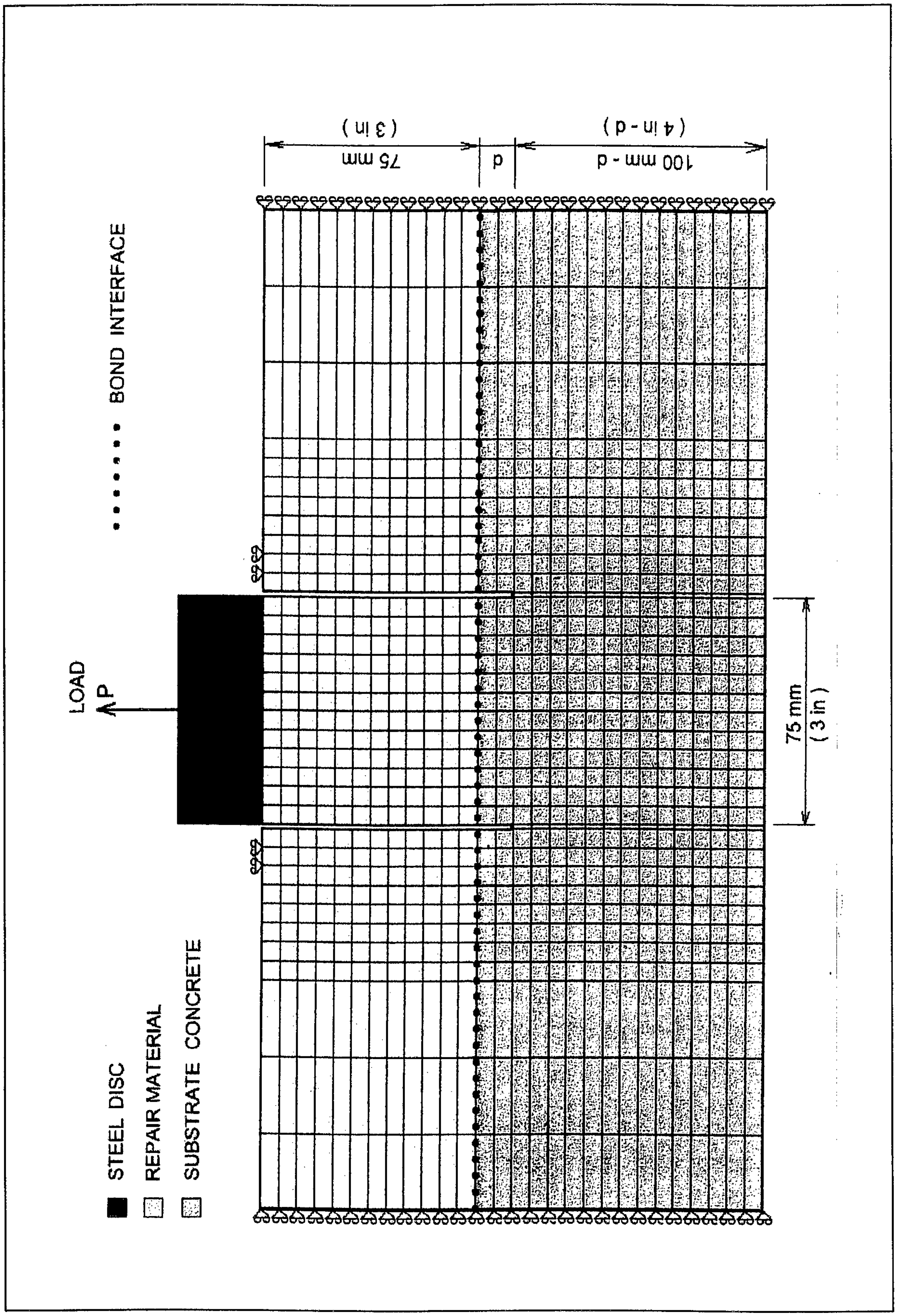


Figure 32. Typical finite-element mesh

of 1,125 joints and 1,028 elements. The differences in partial coring depth (d) were modeled by adding or removing elements.

The values for modulus of elasticity of the repair materials given in Table 21 were obtained from the results of laboratory tests reported by Poston et al. (1998). The moduli of elasticity of the concrete in the substrate and steel disc are also presented in Table 21. The properties of the adhesive have not been included in the model because of the small adhesive thickness and negligible influence on the stress distribution.

Table 21
Materials Moduli of Elasticity Used in Analysis

Material No.	Modulus of Elasticity	
	MPa	psi
2	22×10^3	3.2×10^6
6	36.5×10^3	5.3×10^6
10	29×10^3	4.2×10^6
Concrete Substrate	25×10^3	3.65×10^6
Steel Disc	200×10^3	29×10^6

The applied tensile load was assumed to be a concentrated axial force at the top of the steel disc. The magnitude of the force used in each model was that recorded at failure in experimental field testing. Figures 33-41 represent the stress distributions within the specimens of the experimental repairs based on the finite-element analysis. The stress contours shown in these figures demonstrate the nonuniformity of stresses across the bottom sections of the partial cores.

Typical stress distribution across the core is summarized in Figure 42.

Based on finite-element analysis, an example of stress distribution within the different zones of the core in experimental repair 2C is shown in Figure 43. The example shows that the magnitude of the maximum stress concentration in the vicinity of the core bottom is 2.2 times higher than the result of the pull-off strength at failure—1.9 MPa (275 psi).

Results of the theoretical analysis demonstrates that the shallow depth of core drilling below the bond line puts the bond interface close to the zone of maximum stress concentrations at the bottom of the core, which corresponds to lower failure loads. In the pull-off bond test, deeper drilling into the substrate reduced stress concentrations at the bond interface and increased the measured bond strength.

The results of experimental tests of pull-off bond strength (adhesive failure mode at the interface) are shown in Table 22. This table includes only the test results corresponding to mode of failures at the repair-substrate interface or within 2 mm (1/16-in.) from it. Linear interpolation of these results is shown in Figure 44.

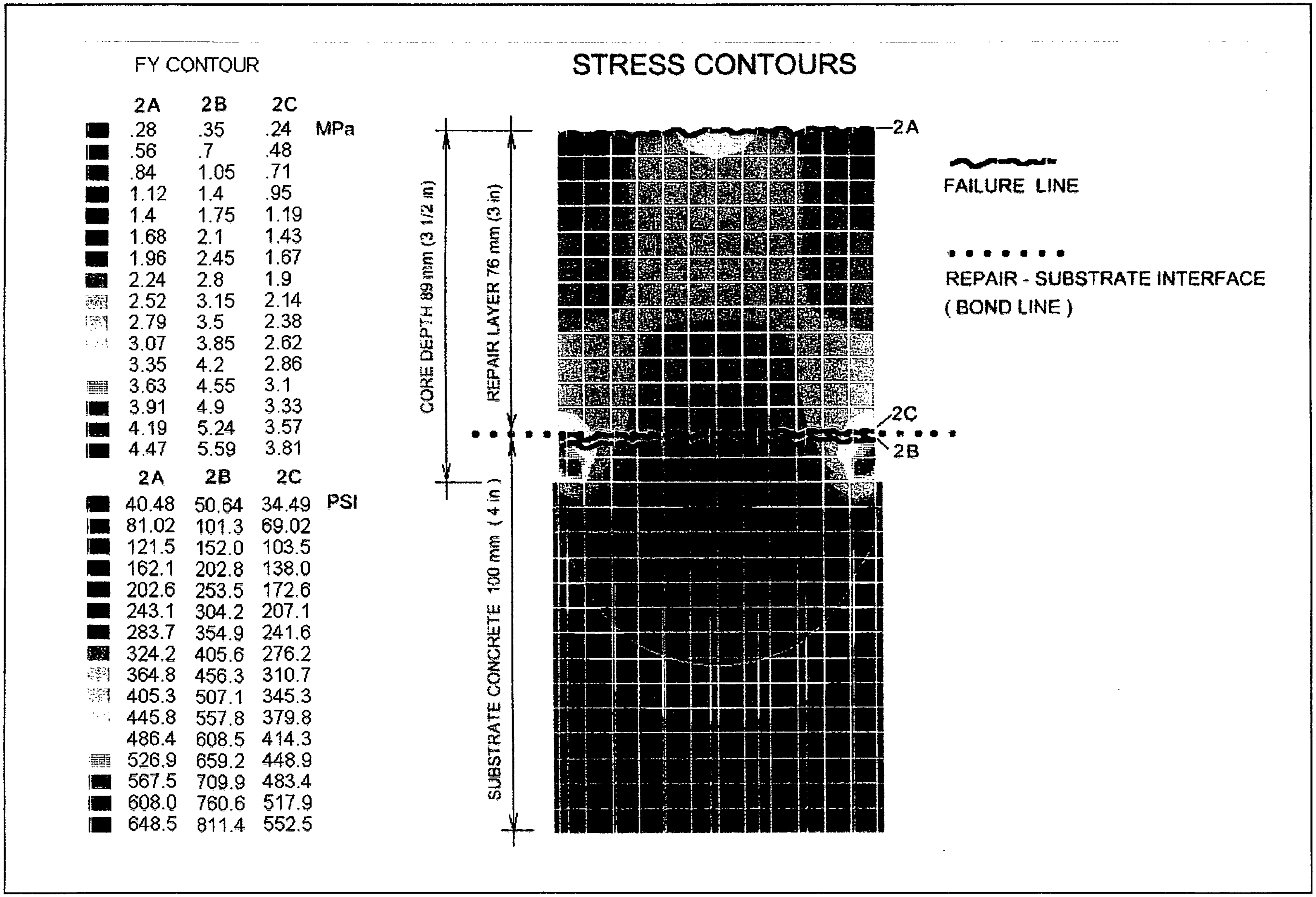


Figure 33. Stress contours—Material No. 2, core depth 89 mm (3-5 in.)

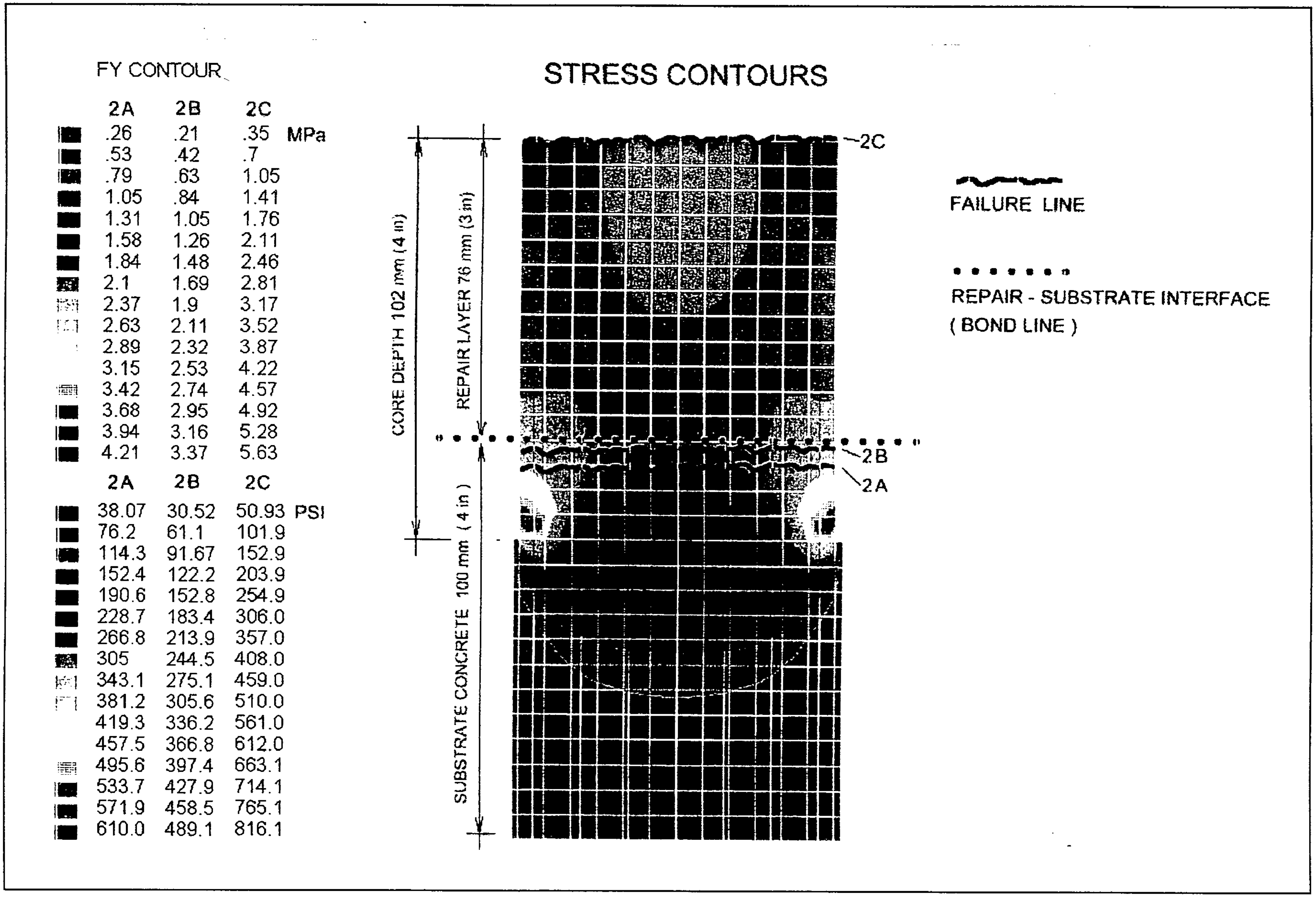


Figure 34. Stress contours—Material No. 2, core depth 101 mm (4 in.)

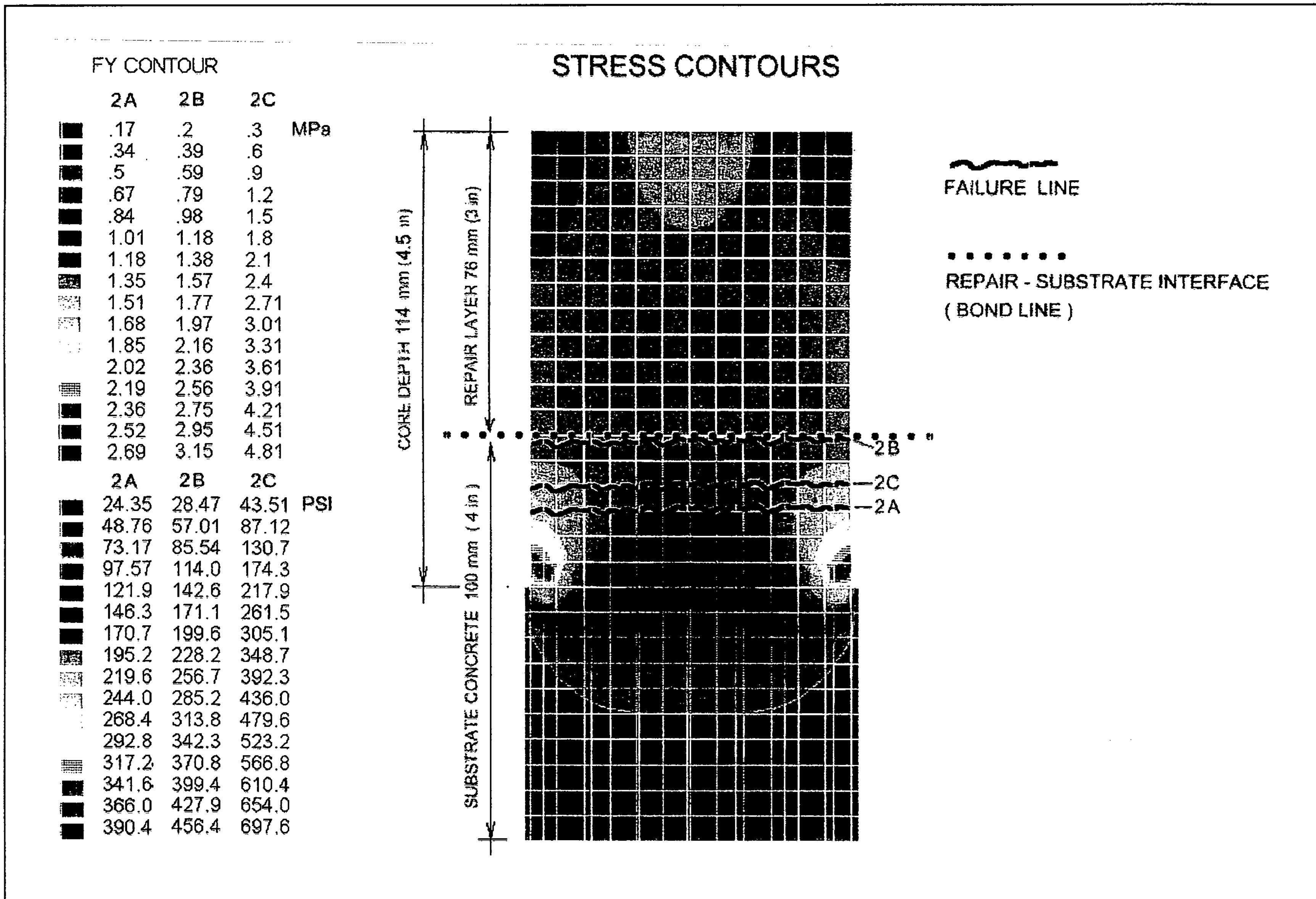


Figure 35. Stress contours—Material No. 2, core depth 114 mm (4.5 in.)

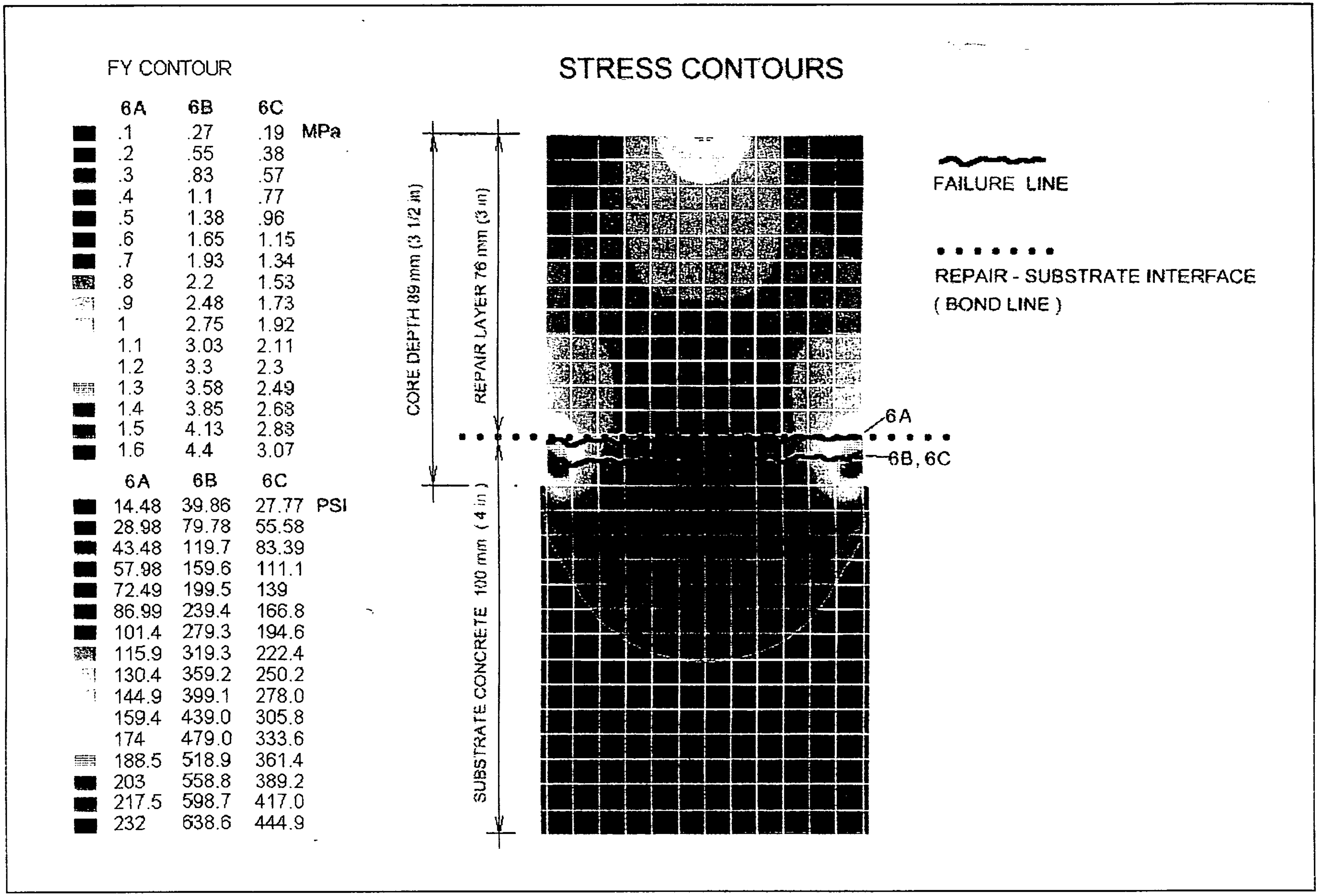


Figure 36. Stress contours—Material No. 6, core depth 89 mm (3.5 in.)

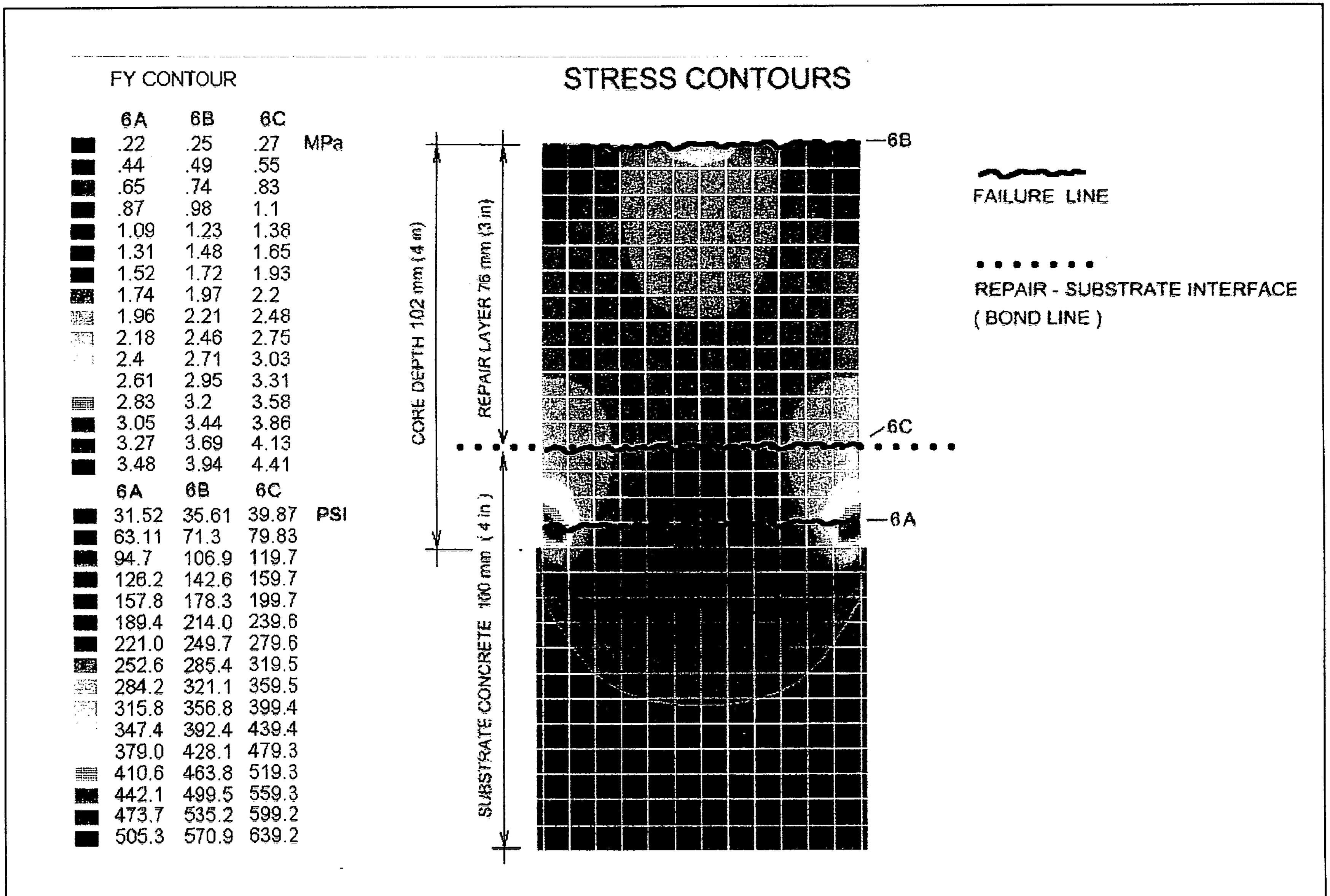


Figure 37. Stress contours—Material No. 6, core depth 101 mm (4-in.)

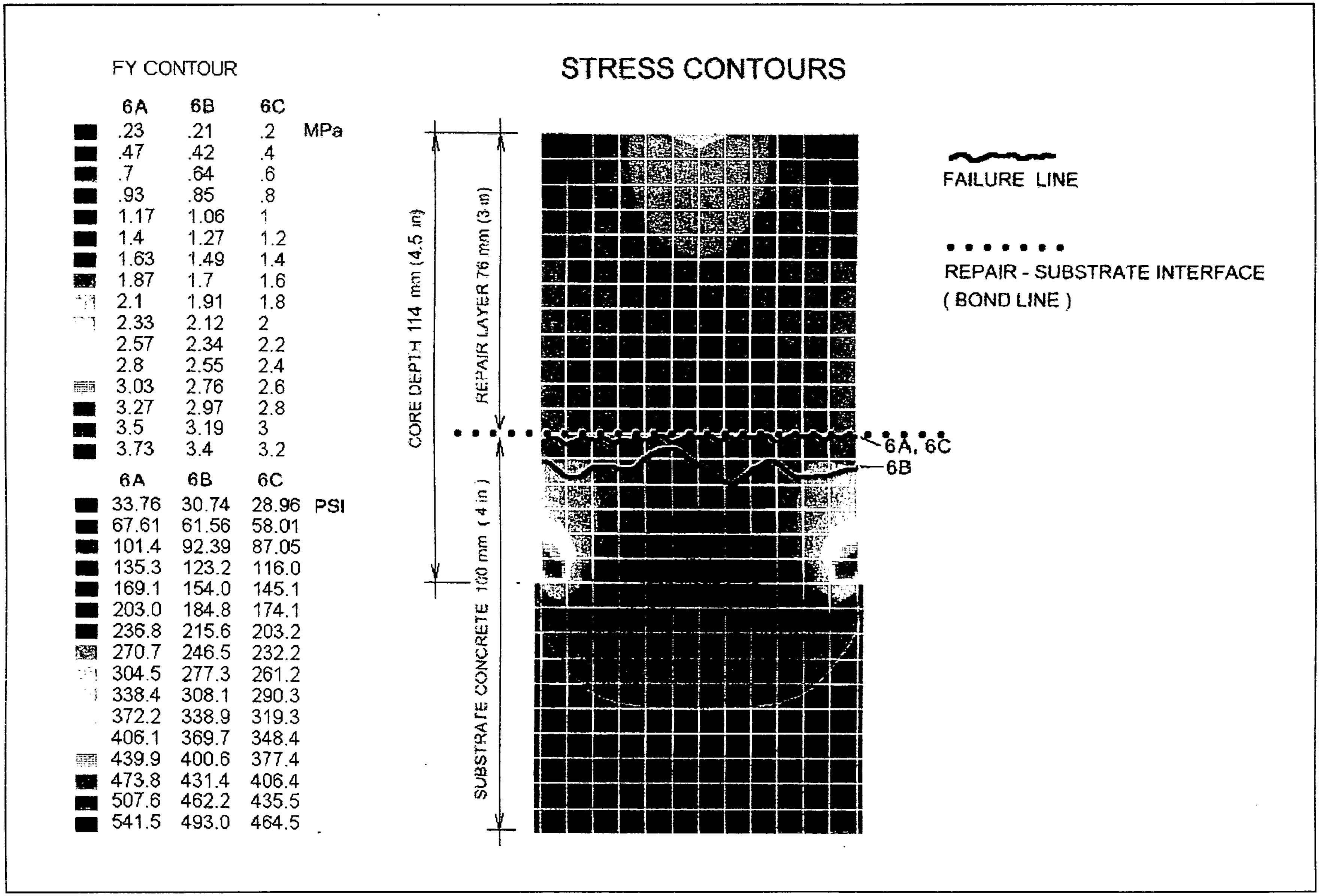


Figure 38. Stress contours—Material No. 6, core depth 114 mm (4.5 in.)

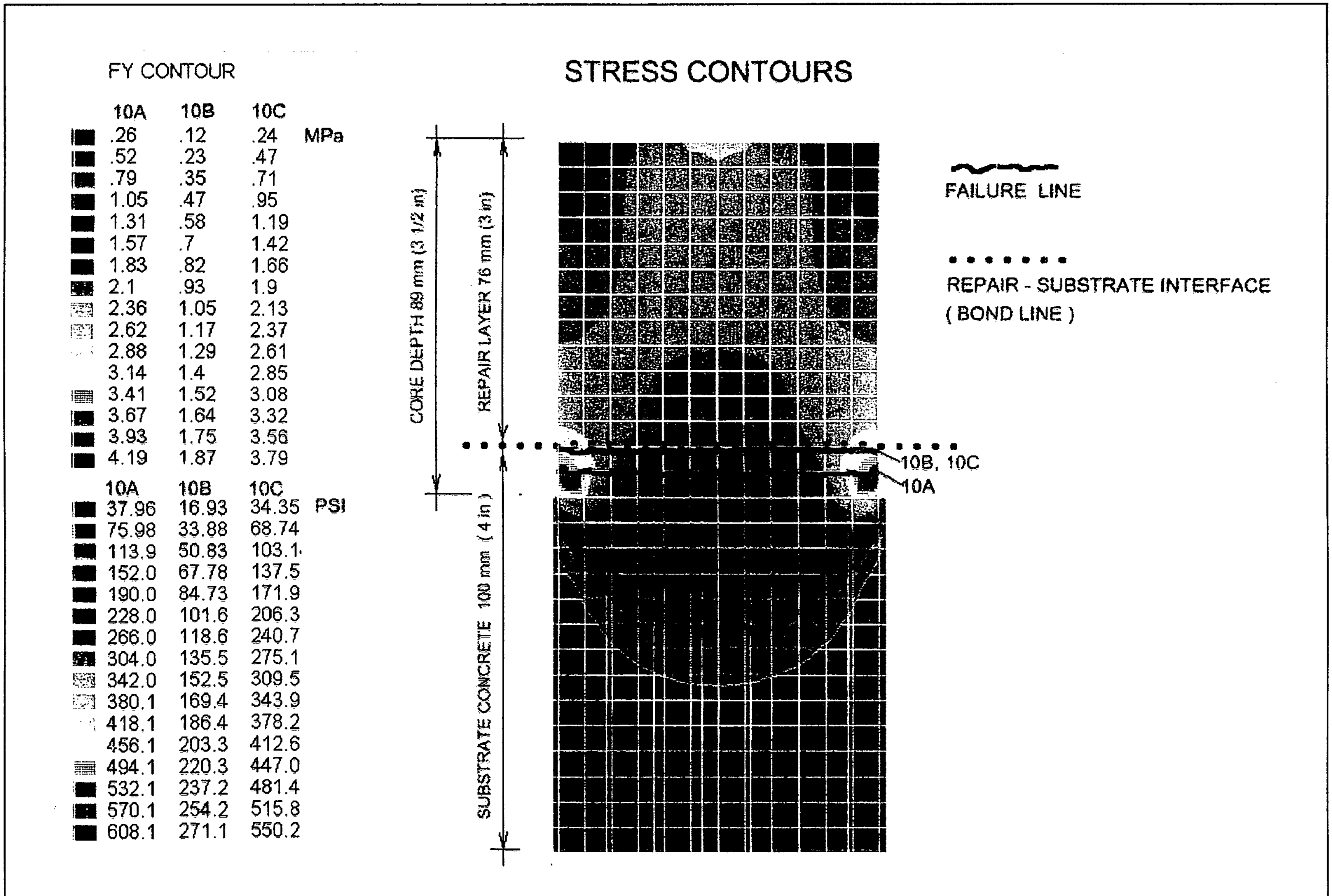


Figure 39. Stress contours—Material No. 10, core depth 89 mm (3.5 in.)

FY CONTOUR

10A	10B	10C	
.13	.22	.13	MPa
.27	.44	.26	
.4	.66	.39	
.54	.89	.52	
.67	1.11	.65	
.81	1.33	.77	
.94	1.55	.9	
1.08	1.77	1.03	
1.21	1.99	1.16	
1.35	2.21	1.29	
1.48	2.44	1.42	
1.62	2.66	1.55	
1.75	2.88	1.68	
1.89	3.1	1.81	
2.02	3.32	1.94	
2.16	3.54	2.07	
10A	**10B**	**10C**	
19.55	32.07	18.69	PSI
39.13	64.19	37.41	
58.71	96.31	56.14	
78.29	128.4	74.86	
97.88	160.5	93.58	
117.4	192.6	112.3	
137.0	224.7	131.0	
156.6	256.9	149.7	
176.2	289.0	168.4	
195.7	321.1	187.1	
215.3	353.2	205.9	
234.9	385.3	224.6	
254.5	417.5	243.3	
274.1	449.6	262.0	
293.6	481.7	280.8	
313.2	513.8	299.5	

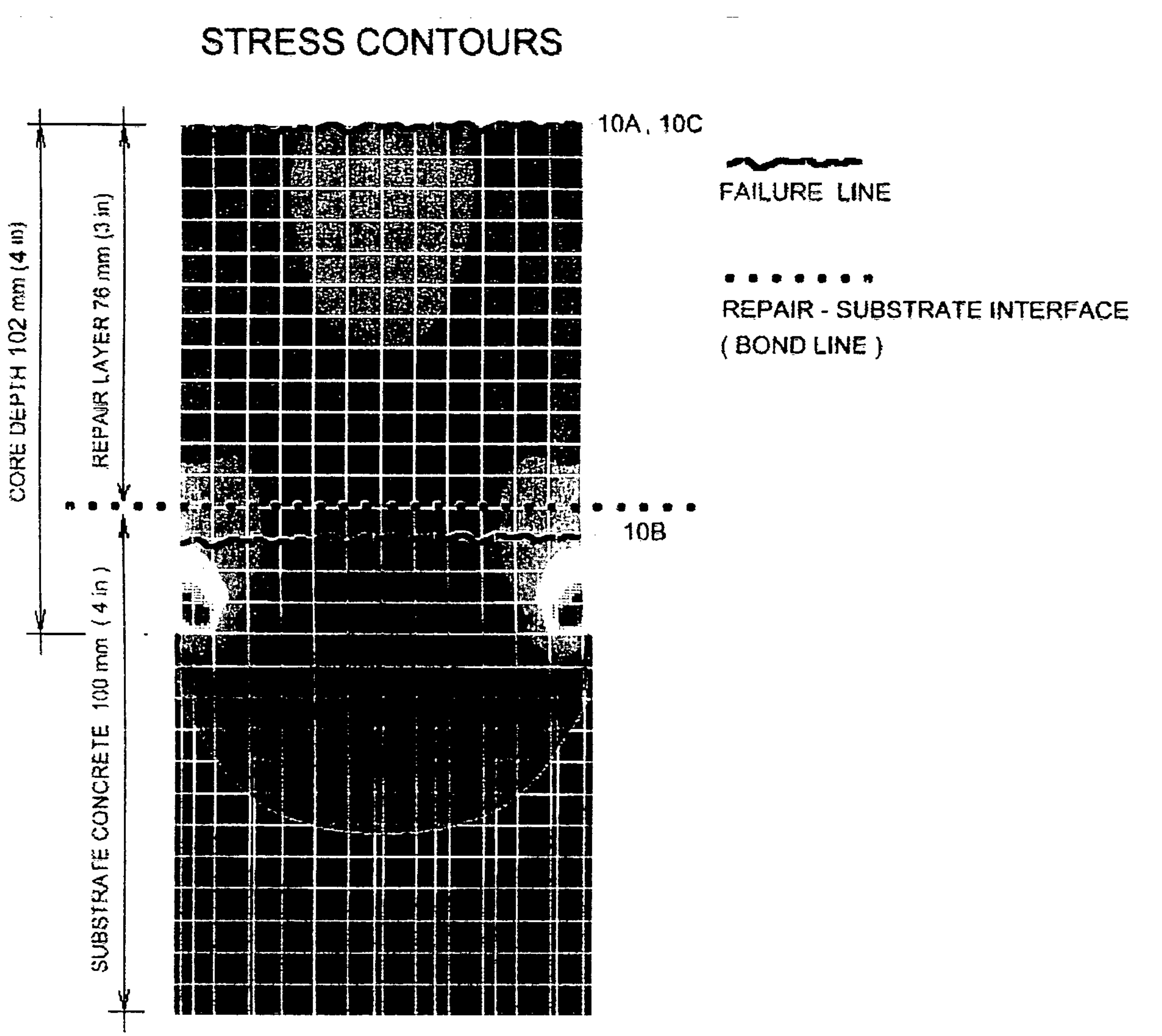


Figure 40. Stress contours—Material No. 10, core depth 101 mm (4-in.)

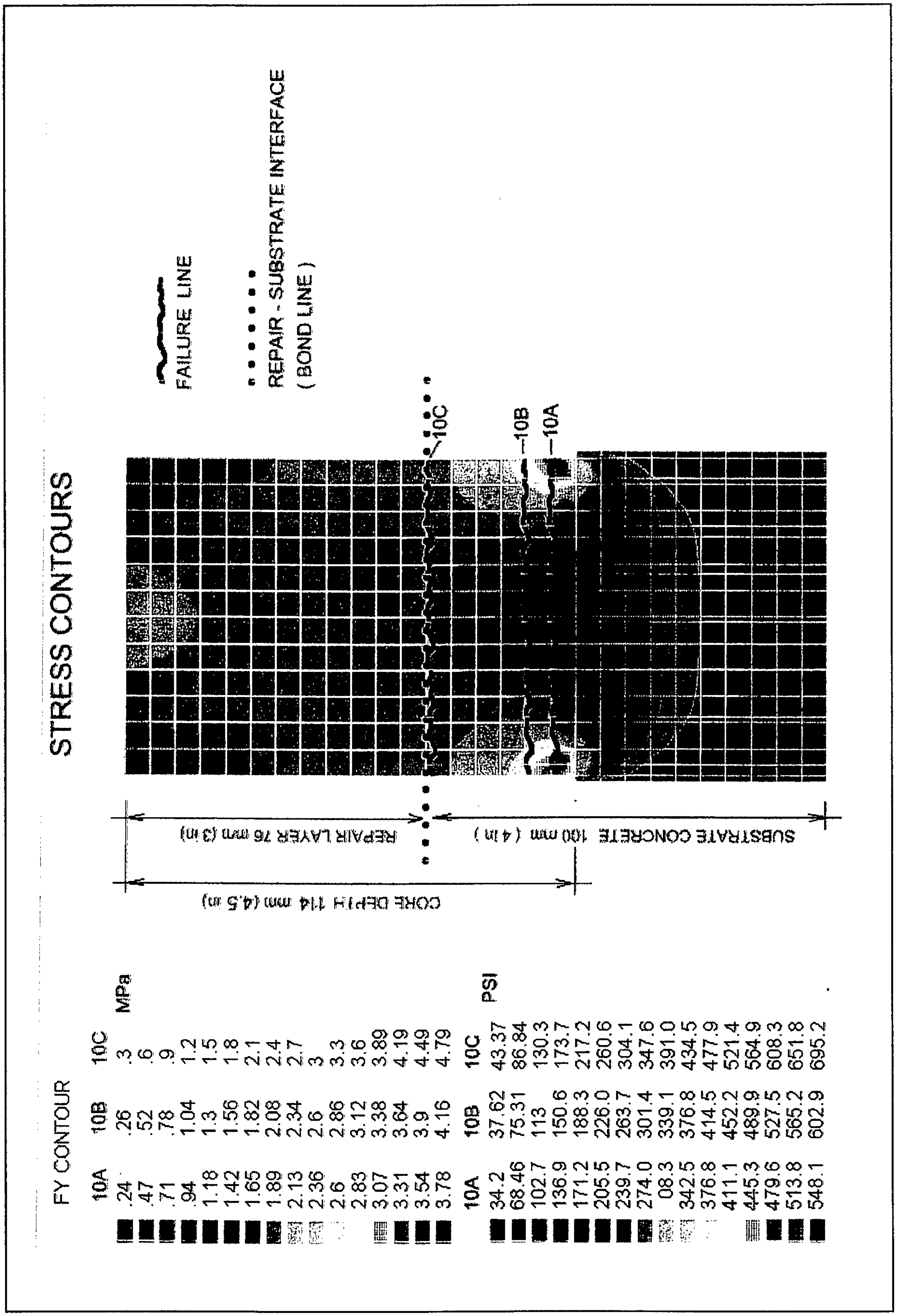


Figure 41. Stress contours—Material No. 10, core depth 114 mm (4-5 in.)

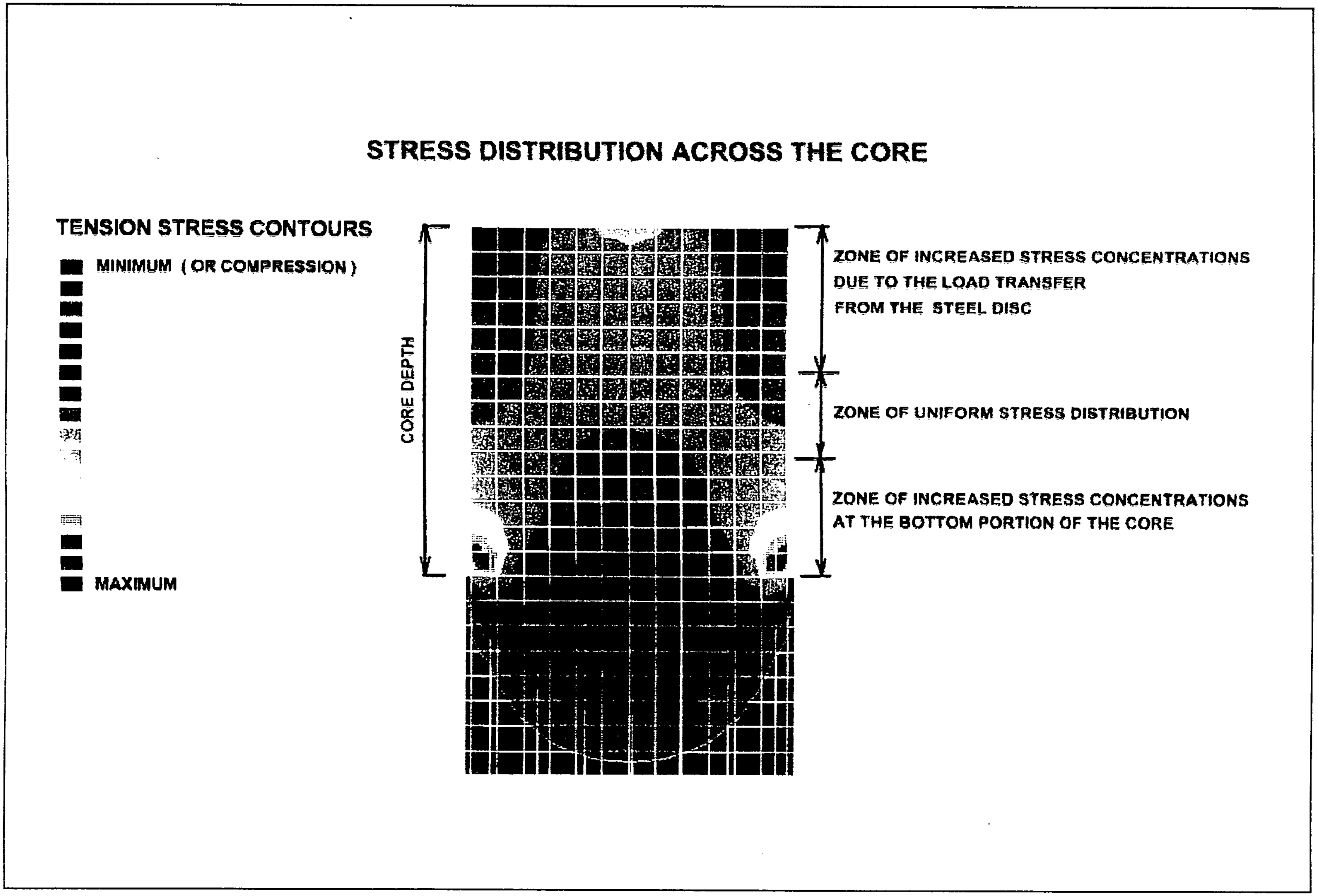


Figure 42. Typical stress distribution across core

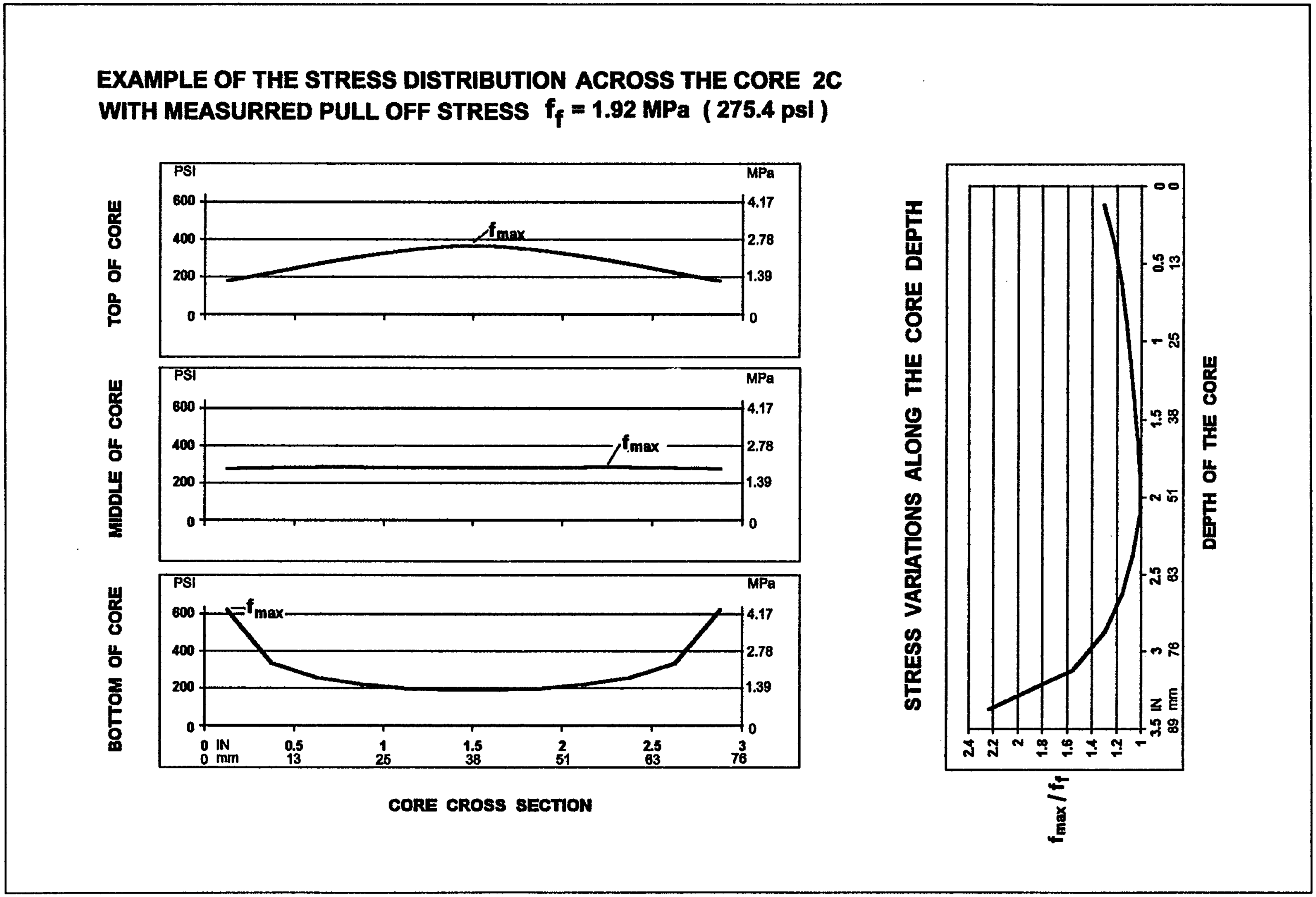


Figure 43. Example of stress distribution in Core 2C

Table 22
Bond Strength Results (Adhesive Failure)

Material Number	Repair Specimen	Bond Strength, MPa (psi) — Core Drilling Depth Below Bond Line, mm (in.) 13 (0.5)	25 (1.0)	37 (1.5)
2	B	-	1.65 (236.8)	1.47 (212.2)
	C	1.92 (275.4)		
6	A	0.80 (113.2)		1.77 (262.8)
	C		2.17 (311.4)	
10	B	0.96 (135.6)		
	C	1.94 (278.4)		2.23 (321.0)

The linear interpolation of the bond strength test results presented in Figure 44, despite the limited amount of real bond failures, confirms the conclusions of the theoretical analysis that shallow core drilling depths into the substrate give rise to significant stress concentrations and underestimate the real bond strength. Although these theoretical analyses relate to only 10 bond failure cases (37 percent of the total amount of pull-off strength tests in this series), they suggest trends that have been confirming the conclusions in other studies (Austin, Robins, and Pan 1995).

Shallow drilling of partial cores into the concrete substrate, when evaluating bond strength in repair systems by the pull-off method, is usually caused by poor workmanship onsite, unawareness of drilling depth effects, ignorance to the issues in specifications, and quality control guidelines. The effect of this may be one of the causes of shortcomings in reproducibility and comparability of pull-off bond test results.

Based on the results of the experiments and theoretical analysis, the suggested core depth below the repair-substrate interface shall be a minimum of 25 mm (1 in.) or one-half of the core diameter, whichever is larger.

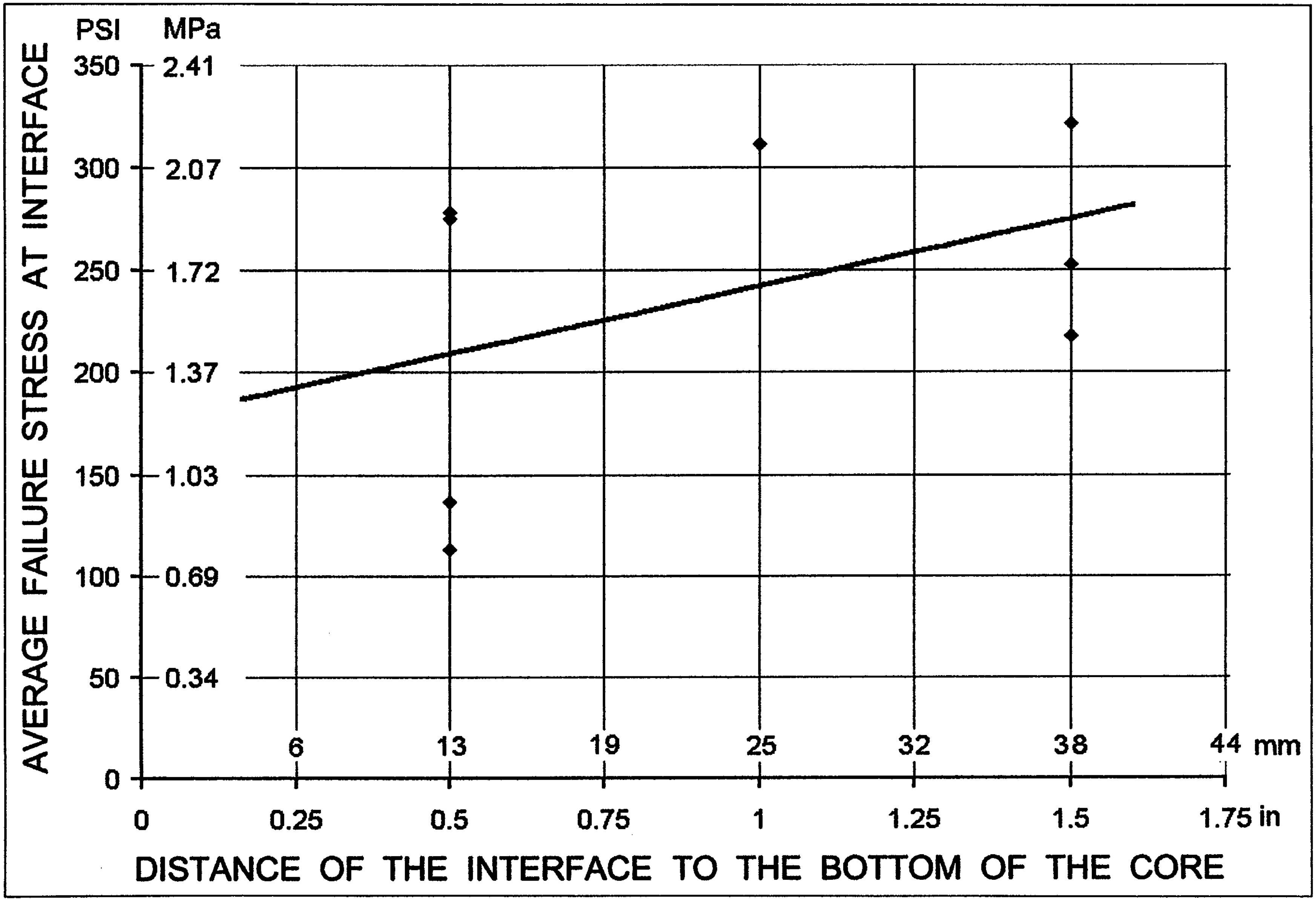


Figure 44. Effect of core drilling depth into substrate on tested bond strength

5 Summary and Conclusions

A field study was conducted to (a) investigate the effect of material properties and environmental conditions on bond strength development for nine repair materials used in experimental repairs; (b) investigate the effect of drilling depth into the substrate concrete on pull-off test results by comparing theoretical finite element analyses of failure stress and location with measured test results and to recommend the optimum depth of core drilling into the existing substrate; and (c) evaluate three commercially available tensile pull-off testing apparatuses for bond testing.

A total of 257 partial-depth cores in 77 experimental repairs were tested in Florida, Illinois, and Arizona in order to examine the effect of material properties and environmental conditions on bond between repair and concrete substrate. Three testing devices were used to determine the bond strengths for each of the experimental repairs. In addition, the testing devices themselves were compared for consistency of data and ease of use in an effort to identify a reliable and practical device for use in the field.

The conclusions from this field study are as follows:

a. In general, the results obtained from the pull-off tests can be described as variable or very variable.

Although the materials tested exhibited a wide range of pull-off strengths, all materials exhibited average strengths in excess of 1.5 MPa (215 psi). There was a clear pattern of preferential failure in the substrate concrete that indicates that the base concrete was generally the weakest link in the tested repair systems.

b. Because of the mixed failure modes, most of the pull-off test results do not provide a value for the tensile bond strength; they provide relative data in this context.

c. In most practical applications, pull-off testing is conducted to determine if the bond strength between repair and concrete substrate meets the specified criteria. In such applications, it is generally desirable for failure to not occur at the repair-substrate interface (adhesive failure). Failure within the repair material or substrate concrete (cohesive failures) or partial failures such as interface-repair or interface-substrate (adhesive/cohesive failure)

are acceptable providing the bond stress is equal to or greater than the specified bond stress. If failure occurs at the steel disc-repair interface, then the pull-off strength result represents a minimum bond strength, and the test should be repeated if the strength is not acceptable.

d. Variations in exposure conditions did not appear to have a significant effect on the failure modes or bond strengths of the repair materials. Adequate curing procedures provided may have significantly contributed to minimizing environmental effects on bond strength development.

e. Again, no obvious explanation exists regarding the fact that no correlation was found between tensile strength, shrinkage, modulus of elasticity, and thermal expansion properties of the repair materials measured in the laboratory and their tensile bond strength to the concrete substrate. At the same time, surprisingly there was some correlation between compressive and flexural strengths determined in the laboratory and field pull-off strengths.

f. The study demonstrated that two of the three pull-off test devices, Germann Instruments Bond-Test and Proceq DYNA Z15, can be used to evaluate the tensile bond strength of repairs, to accept or reject an installation, and to gain information on the possible weakening or deterioration of the repair-substrate bond with time.

g. Results of the present study indicate that the critical requirements for pull-off test apparatuses are as follows:

(1) Gradually increasing load must be applied at a specified rate of loading.

(2) Load must be applied at a right angle to the repair surface under test.

(3) The pull-off failure stress attained should be accurately recorded.

(4) The apparatus should be self-contained and portable for field site tests.

h. Depth of the partial core drilling into the substrate may significantly affect the results of the pull-off tests. The findings of the present study emphasize the importance of standardization of the core depth beyond the repair-substrate interface for pull-off bond test. The depth of core drilling below the interface should be a minimum of 25 mm (1-in.) or one-half of the core diameter, whichever is larger.

i. Differences in the theoretical finite element analysis and observed field behavior may be attributed to at least four effects: the presence of flaws in the system, stress relief caused by strain relief, the probability that the weakest zone does not correspond with the area of highest stress, and relative sensitivity of the testing device to the rate of loading and deviation from the normal angle to the surface.

j. What has been learned from this study regarding the effect of various factors on the repair-substrate bond strength from the study that has been described? Aside from the influence of the combination of properties of the repair material and substrate concrete, depth of partial core drilling into the substrate, and the precision of the testing equipment, one of the most significant influences is the workmanship during the repair application, which often completely overshadows all other variables.

6 Recommendations

The tensile pull-off test is recommended as the best available test method for monitoring bond strengths in the field, although the results of this test do not necessarily indicate precise tensile bond values. However, the procedures and equipment for conducting tensile pull-off bond tests on concrete repairs and overlays should be standardized. In the absence of standardization, it is strongly recommended that the particular test equipment and configuration are clearly specified when setting minimum acceptable values of the pull-off strength for use in a particular repair or overlay project. The pull-off equipment must be such that the direction of tensile force is at right angles to the surface in order to achieve uniaxial tension. The equipment must be capable of steadily increasing the load without jerking at an approximate rate range of 0.02 to 0.05 N/mm^2 (3 to 7 psi) per second. The pull-off equipment must be capable of recording the failure stress to the nearest 0.1 N/mm^2 (15 psi). The depth of core drilling below the repair-substrate interface should be to a minimum of 25 mm (1-in.) or one-half the core diameter, whichever is larger. The steel disc must be attached centrally to the partial core surface. When failure occurs at the interface between the repair surface and the steel disc, the failure stress shall be considered as a minimum bond strength value. If this minimum value does not satisfy the required bond strength, then the test should be repeated. Additional theoretical analyses, such as finite element analysis, which take into account differences in properties of a repair material and base concrete such as strengths, stiffness, and volume changes, should be performed to provide additional information on stress distribution and failure modes. Pull-off test equipment for determining the in situ tensile bond strength of repairs on surfaces other than horizontal should be identified and evaluated. The effect of the core drilling technique and type of equipment on pull-off test results should be investigated. In addition to the uniaxial pull-off tensile bond test method studied in this report, the relative merits of other bond test methods such as direct shear and torsion test methods should be evaluated.

References

American Society for Testing and Materials. (1995). "Standard specification for epoxy-resin based bonding systems for concrete," ASTM C 881, *Annual Book of ASTM Standards*, Philadelphia, PA.

Austin, S., Robins, P., and Pan, V. (1995). "Tensile bond testing of concrete repairs," *Materials and Structures* (28), 249-259.

British Standard BS 1881: Part 207. (1992). "Recommendations for the assessment of concrete strength by near-to-surface tests."

Bungey, J. H., and Mandandoust, R. (1992). "Influencing pull-off tests in concrete," *Magazine of Concrete Research* 44(158), 21-30.

Collins, F. G., and Roper, H. (1989). "Evaluation of concrete spall repairs by pullout test," *Materials and Structures* 22, RILEM, 280-286.

Dutch Standard. (1990). "Determination of the bond strength of mortars on concrete," CUR Recommendations 20, Centre for Civil Engineering, Research, Codes and Specifications.

Emmons, P. H., Vaysburd, A. M., Poston, R. W., and McDonald, J. E. (1998). "Performance criteria for concrete repair materials, Phase II, field studies" Technical Report REMR-CS-60, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Knab, L. I. (1988). "Factors related to the performance of concrete repair materials," Technical Report REMR-CS-12, U.S. Army Corps of Engineers, Washington, DC.

Li, S., Frantz, C., and Stephens, J. E. (1997). "Application of pull-off test to access the durability of bond between new and old concrete subjected to deicer salts," ACI SP-168, 267-294.

Long, A. E., and Murray, A. (1984). "The pull-off partially destructive test for concrete," ACI SP-82, 327-350.

Mathey, R. G., and Knab, L. I. (1991). "Uniaxial tensile tested to measure the bond of in-situ concrete overlays," NISTIR 4648.

McLeish, A. (1993). "Standard tests for repair materials and coatings for concrete, Part I: Pull-off tests," Technical Note 139, CIRIA.

Peterson, C. G. (1990). "New bond testing method developed," *ICRI Concrete Bulletin*.

Poston, R. W., Kesner, K. E., Emmons, P. H., and Vaysburd, A. M. (1998). "Performance criteria for selection of repair materials, Phase II laboratory results," Technical Report REMR-CS-57, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Rizzo, E. M., and Sobelman, M. (1989). "Selection criteria for concrete repair materials," *Concrete International* 11(9), 46-49.

Stehno, G., and Mall, G. (1977). "The tear-off method – a new way to determine the quality of concrete in structures on site," RILEM International, Symposium on Testing In Situ of Concrete Structures, Budapest, 335-347.

Appendix A
Pull-Off Test Data

Table A1
Pull-Off Test Data (Florida)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure
			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi	
1	1A	9.8	2.17	314	Repair-substrate interface	3.6	1.78	254	Repair-substrate interface	680	1.49	217	Top surface (skin) of repair
	1B	13.2	2.93	424	½" in substrate	4.0	1.97	281	Repair-substrate interface	780	1.71	248	Top surface (skin) of repair
	1C	7.5	1.65	240	Repair-substrate interface	3.2	1.58	225	Repair-substrate interface	640	1.40	204	Top surface (skin) of repair
2	2A	7.3	1.61	233	Repair-substrate interface	4.2	2.07	295	1/16" in substrate	990	2.17	315	Repair-substrate interface
	2B	8.1	1.79	259	Disk-repair interface (epoxy)	3.7	1.83	261	Repair-substrate interface	960	2.11	306	2" in substrate
	2C	11.3	2.50	363	Repair-substrate interface	4.7	2.32	331	Repair-substrate interface	1,100	2.41	350	1" in substrate
3	3A	8.2	1.81	262	1/32" from repair top	3.4	1.68	240	½" from repair top	560	1.23	178	2½" from repair top
	3B	9.2	2.03	295	Repair surface	3.6	1.78	254	¼" from repair top	600	1.32	191	2½" from repair top
	3C	8.5	1.88	272	2½" - 2¾" from repair top	3.2	1.58	225	2" from repair top	540	1.19	172	2¾" from repair top

Sheet 1 of 3

Table A1 (Continued)

Material	Repair Specimen	Germann Instruments Bond-Test: Pull-Off Force kN	Pull-Off Strength MPa (N/mm²)	Pull-Off Strength psi	Mode of Failure	Proceq DYNA Z15: Pull-Off Force kN	Pull-Off Strength MPa (N/mm²)	Pull-Off Strength psi	Mode of Failure	Hilti Tester 4 (Modified): Pull-Off Force kN	Pull-Off Strength MPa (N/mm²)	Pull-Off Strength psi	Mode of Failure
4	4A	15.7	3.49	505	¼" in substrate	6.4	3.16	451	1/8" in substrate	1,200	2.63	382	¼" in substrate
	4B	0	0	0	No bond	6.1	3.01	429	1/16" in substrate	1,100	2.41	350	Repair-substrate interface
	4C	14.9	3.31	479	¼" in substrate	6.0	2.96	422	1/16" in substrate	1,100	2.41	350	¼" in substrate
6	6A	16.7	3.71	538	¼" in substrate	6.4	3.16	451	1" in substrate	770	1.69	245	¾" in substrate
	6B	15.4	3.42	496	1/8" in substrate	5.9	2.91	415	1" in substrate	750	1.65	239	½" in substrate
	6C	14.4	3.19	463	1/8" in substrate	6.1	3.01	429	½" in substrate	850	1.87	271	1" in substrate
8	8A	8.4	1.85	269	1/16" - 1/8" from repair top	3.2	1.58	225	Repair-substrate interface	760	1.67	242	1" from repair top
	8B	6.2	1.36	198	Repair-substrate interface	3.0	1.48	211	Repair-substrate interface	850	1.87	271	1/16" from repair top
	8C	9.5	2.10	305	1/16" - 1/8" from repair top	3.7	1.83	261	½" in substrate	800	1.76	255	½" - 1" in substrate

Sheet 2 of 3

Table A1 (Concluded)

		Germann Instruments Bond-Test				Proceq DYNA Z16				Hilti Tester 4 (Modified)			
		Pull-Off Force	Pull-Off Strength			Pull-Off Force	Pull-Off Strength			Pull-Off Force	Pull-Off Strength		
Material	Repair Specimen	kN	MPa (N/mm^2)	psi	Mode of Failure	kN	MPa (N/mm^2)	psi	Mode of Failure	kN	MPa (N/mm^2)	psi	Mode of Failure
9	9A	1.0	0.20	29	Repair-substrate interface	0.9	0.44	63	Repair-substrate interface	150	0.33	48	Repair-substrate interface
	9B	2.4	0.51	75	Repair-substrate interface	1.3	0.64	91	Repair-substrate interface	190	0.42	61	Repair-substrate interface
	9C	2.4	0.51	75	Repair-substrate interface	1.1	0.54	77	Repair-substrate interface	220	0.48	70	Repair-substrate interface
10	10A	8.1	1.79	259	1½" in substrate	3.9	1.92	274	1" in substrate	780	1.71	248	1½" in substrate
	10B	9.6	2.12	308	Repair-substrate interface	3.6	1.78	254	1/16" in substrate	720	1.58	229	Repair-substrate interface
	10C	10.2	2.26	327	1/8" in substrate	3.9	1.92	274	1/16" in substrate	850	1.87	271	1/8" in substrate
11	11A	13.1	2.90	421	1½" from repair top	6.1	3.01	429	½" in substrate	1,100	2.41	350	Repair-substrate interface
	11B	11.8	2.61	379	Repair-substrate interface	5.4	2.66	379	Repair-substrate interface	970	2.13	309	1/32" in substrate
	11C	11.8	2.61	379	Repair-substrate interface	5.8	2.86	408	1/8" in substrate	1,000	2.19	318	½" in substrate

Sheet 3 of 3

Table A2
Pull-Off Test Data (Illinois)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure
1	1A	6.2	1.39	198	Top surface (skin) of repair	3.5	1.73	253	½" in substrate	640	1.40	204	Disk-repair interface (epoxy)
1	1B	2.7	0.60	84	Repair-substrate interface	0.8	0.39	58	Repair-substrate interface	0	0	0	No bond
1	1C	10.7	2.39	343	Repair-substrate interface	3.0	1.48	218	Repair-substrate interface	580	1.27	185	Top surface (skin) of repair
2	2A	15.0	3.35	483	½" in substrate	4.9	2.42	355	½" in substrate	600	1.32	191	Disk-repair interface (epoxy)
2	2B	12.5	2.79	402	1½" in substrate	5.0	2.47	363	½" in substrate	600	1.32	191	Disk-repair interface (epoxy)
2	2C	12.4	2.77	398	¼" in substrate	3.8	1.87	276	½" in substrate	540	1.19	172	Disk-repair interface (epoxy)
3	3A	7.4	1.65	237	1" from repair top	2.0	0.99	155	2" from repair top	480	1.05	153	1¼" from repair top
3	3B	7.4	1.65	237	Top surface (skin) of repair	3.6	1.78	260	½" from repair top	320	0.70	102	Repair-substrate interface
3	3C	9.2	2.06	295	¼"-3/8" from repair top	2.8	1.38	203	1/16" from repair top	400	0.88	127	Repair-substrate interface

Sheet 1 of 3

Table A2 (Continued)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure
			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi	
4	4A	14.7	3.28	473	¼" in substrate	6.4	3.16	463	1" from repair top	800	1.76	255	Disk-repair interface (epoxy)
	4B	14.4	3.22	463	1/8" in substrate	4.9	2.42	355	½" in substrate	760	1.67	242	½" in substrate
	4C	12.4	2.77	399	1/8" in substrate	5.6	2.76	405	½" in substrate	780	1.71	248	1/8" in substrate
6	6A	12.4	2.77	399	½" in substrate	5.0	2.47	361	1" in substrate	600	1.32	191	½" in substrate
	6B	7.2	1.61	230	Disk-repair interface (epoxy)	1.0	0.49	73	¼' in substrate	520	1.14	166	1/8" in substrate
	6C	13.2	2.95	424	½" in substrate	5.6	2.76	405	1/16" in substrate	700	1.54	223	Disk-repair interface (epoxy)
8	8A	8.0	1.79	256	Top surface (skin) of repair	5.0	2.47	361	Repair-substrate interface	440	0.97	140	Top surface (skin) of repair
	8B	6.2	1.39	198	Top surface (skin) of repair	5.2	2.56	377	Disk-repair interface (epoxy)	500	1.10	159	Top surface (skin) of repair
	8C	7.9	1.77	253	Top surface (skin) of repair	4.7	2.32	340	Repair-substrate interface	440	0.97	140	Top surface (skin) of repair

Sheet 2 of 3

Table A2 (Concluded)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure	Pull-Off Force kN	Pull-Off Strength		Mode of Failure
			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi			MPa (N/mm^2)	psi	
9	9A	3.8	0.85	120	2" from repair top	3.5	1.73	253	2½" from repair top	780	1.71	248	Disk-repair interface (epoxy)
	9B	12.2	2.73	392	2" from repair top	4.3	2.12	311	2" from repair top	620	1.36	197	Disk-repair interface (epoxy)
	9C	11.0	2.44	353	Repair-substrate interface	3.9	1.92	283	½" in substrate	580	1.27	185	1½" from repair top
10	10A	10.2	2.28	327	1/8" in substrate	3.0	1.48	218	½" in substrate	800	1.76	255	Disk-repair interface (epoxy)
	10B	10.2	2.28	327	1/8" in substrate	4.0	1.47	290	½" in substrate	600	1.32	191	1/8" in substrate
	10C	6.8	1.52	217	¼" in substrate	4.8	2.37	347	½" in substrate	800	1.76	255	Disk-repair interface (epoxy)
11	11A	12.8	2.86	411	Repair-substrate interface	6.0	2.46	435	¼" from repair top	500	1.10	159	1/8" in substrate
	11B	12.6	2.82	405	Repair-substrate interface	5.8	2.86	419	1/8" from repair top	-	-	-	Not tested
	11C	8.2	1.83	262	2-3/4" from repair top	5.3	2.61	384	Repair-substrate interface	660	1.45	210	½" in substrate

Sheet 3 of 3

Table A3
Pull-Off Test Data (Arizona)

Material	Repair Specimen	Germann Instruments Bond-Test: Pull-Off Force kN	Germann: Pull-Off Strength MPa (N/mm^2)	Germann: Pull-Off Strength psi	Germann: Mode of Failure	Proceq DYNA Z15: Pull-Off Force kN	Proceq: Pull-Off Strength MPa (N/mm^2)	Proceq: Pull-Off Strength psi	Proceq: Mode of Failure	Hilti Tester 4 (Modified): Pull-Off Force kN	Hilti: Pull-Off Strength MPa (N/mm^2)	Hilti: Pull-Off Strength psi	Hilti: Mode of Failure
1	1A	0	-	-	No bond	3.4	1.68	247	Disk-repair interface (epoxy)	500	1.10	159	Disk-repair interface (epoxy)
	1B	6.8	1.52	217	Repair-substrate interface	4.6	2.27	334	Repair-substrate interface	500	1.10	159	Disk-repair interface (epoxy)
	1C	9.7	2.17	309	Repair-substrate interface	3.0	1.48	218	Top surface (skin) of substrate	600	1.32	191	Disk-repair interface (epoxy)
2	2A	10.1	2.23	324	Disk-repair interface	5.6	2.76	406	Top surface (skin) of substrate	1,100	2.41	350	Disk-repair interface (epoxy)
	2B	12.6	2.79	405	1/8" in substrate	5.0	2.47	363	Top surface (skin) of substrate	900	1.96	287	Disk-repair interface (epoxy)
	2C	8.6	1.90	275	Repair-substrate interface	5.8	2.86	421	¼" in substrate	1,000	2.19	318	Disk-repair interface (epoxy)
3	3A	6.4	1.41	204	Repair-substrate interface	2.4	1.18	174	Repair-substrate interface	500	1.10	159	2" from repair top
	3B	9.8	2.17	314	1" from repair top	2.4	1.18	174	2¾" from repair top	550	1.21	175	2½" from repair top
	3C	9.4	2.08	301	Repair-substrate interface	3.2	1.58	232	2¾" from repair top	670	1.47	213	Repair-substrate interface

Sheet 1 of 3

Table A-3 (Continued)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure
4	4A	4.9	1.07	156	Disk-repair interface (epoxy)	3.6	1.78	261	¼" in substrate	900	1.98	287	Disk-repair interface (epoxy)
	4B	2.7	0.58	84	Repair-substrate interface	4.0	1.47	290	Top surface (skin) of substrate	700	1.54	223	Disk-repair interface (epoxy)
	4C	4.7	1.03	149	Repair-substrate interface	5.2	2.57	377	1/16" in substrate	700	1.54	223	Disk-repair interface (epoxy)
6	6A	3.6	0.78	113	Top surface (skin) of substrate	3.8	1.87	276	Top surface (skin) of substrate	560	1.23	178	Disk-repair interface (epoxy)
	6B	9.7	2.14	311	¼" in substrate	3.2	1.58	232	Repair-substrate interface	200	0.44	64	Repair-substrate interface
	6C	6.8	1.50	217	¼" in substrate	4.0	1.47	290	Top surface (skin) of substrate	650	1.43	207	Repair-substrate interface
8	8A	8.8	1.94	282	Disk-repair interface (epoxy)	3.6	1.78	261	Repair-substrate interface	600	1.32	191	Disk-repair interface
	8B	10.4	2.30	334	Top surface (skin) of repair	2.8	1.38	203	Repair-substrate interface	620	1.36	197	Top surface (skin) of repair
	8C	8.6	1.90	275	Top surface (skin) of repair	3.5	1.73	253	Repair-substrate interface	700	1.54	223	Top surface (skin) of repair

Sheet 2 of 3

Table A-3 (Concluded)

Material	Repair Specimen	Germann Instruments Bond-Test				Proceq DYNA Z15				Hilti Tester 4 (Modified)			
		Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure	Pull-Off Force kN	Pull-Off Strength MPa (N/mm^2)	Pull-Off Strength psi	Mode of Failure
9	9A	6.6	1.45	211	Repair-substrate interface	5.2	2.57	377	1/8" in substrate	800	1.76	255	1/2" in substrate
	9B	8.5	1.88	272	Repair-substrate interface	5.6	2.76	406	1/16" in substrate	800	1.76	255	Repair-substrate interface
	9C	11.0	2.44	353	Repair-substrate interface	5.0	2.47	363	Repair-substrate interface	900	1.98	287	Disk-repair interface (epoxy)
10	10A	9.6	2.12	308	1/4" in substrate	4.0	1.97	290	1/16" in substrate	600	1.32	191	1/4" in substrate
	10B	4.3	0.94	136	Top surface (skin) of repair	2.4	1.18	174	0 – 1/4" in substrate	660	1.45	210	Disk-repair interface (epoxy)
	10C	8.7	1.92	279	Top surface (skin) of repair	3.6	1.78	261	0 – 1/4" in substrate	600	1.32	191	Disk-repair interface (epoxy)
11	11A	9.1	2.01	292	1/8" in substrate	4.0	1.97	290	1/16 – 1/2" in substrate	775	1.70	247	1/2" in substrate
	11B	10.4	2.30	334	1/8" in substrate	4.0	1.97	290	1/16 – 1/4" in substrate	775	1.70	247	Disk-repair interface (epoxy)
	11C	10.3	2.28	330	1/8" in substrate	5.2	2.57	377	1/2 – 1" in substrate	900	1.98	287	1/4" in substrate

Sheet 3 of 3

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1999

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
An Evaluation of Equipment and Procedures for Tensile Bond Testing of Concrete Repairs

5. FUNDING NUMBERS

6. AUTHOR(S)
Alexander M. Vaysburd, James E. McDonald

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Structural Preservation Systems, Inc., 3761 Commerce Drive, Suite 414, Baltimore, MD 21227; U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report REMR-CS-61

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

If the durability of repaired concrete structures is a primary objective of any repair project, then every effort should be made to ensure adequate bonding between the repair and the existing concrete substrate. A total of 257 partial-depth cores in 77 experimental repairs were tested in Florida, Illinois, and Arizona in order to evaluate the effect of material properties and environmental conditions on the bond between repair and concrete substrate. Three pull-off testing devices were used to determine the bond strengths for each of the experimental repairs. In addition, the testing devices themselves were evaluated by analyzing the magnitude and relative precision of the pull-off strengths, modes of failure, and ease of use in an effort to identify a reliable and practical device for determining in situ tensile bond. The optimum depth of core drilling into the existing substrate was determined by comparing theoretical finite element analysis of failure zone stress distribution with measured test results.

14. SUBJECT TERMS

Concrete structures	Repair
Core drilling	Repair materials
Exposure tests	Tensile bond strength
Pull-off testing devices	

15. NUMBER OF PAGES
84

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT